A review of tropical dry forest ecosystem service research in the Caribbean – gaps and policy-implications

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Abstract

Tropical dry forests (TDFs) are globally threatened, yet remain poorly studied. In the Caribbean, the most biodiverse of island biodiversity hotspots, TDFs have structural properties distinct from the Neotropical mainland and are important to local communities for ecosystem services. We undertook a systematic review (n = 186) on the ecosystem services literature of Caribbean TDF. Only 19.89% qualified for inclusion, with the majority (43.24%) from grey literature. Research on supporting services (31.14%), particularly primary production was predominant. Most studies (70.97%) took a biophysical perspective and quantification often focused on the supply of ecosystem services (43.00%), while measurement of wellbeing benefits were uncommon. Geographic coverage of all studies was patchy originating from only nine of 28 independent countries and dependent territories. Our findings highlight a lack of research, while accentuating the value of grey literature in quantifying ecosystem services. Of particular concern, are gaps in water- and air-related services and the importance of TDF to human health. To move from biophysical assessments to a broader portfolio of ecosystem services valuation studies, research on Caribbean TDF should be collaborative and strategic. Such gaps and research biases suggest key opportunities for evidence-led policy-making. These lessons are of relevance for mainstreaming ecosystem services into decision-making in Small Island Developing States.

Keywords: Caribbean, dry forest, ecosystem services, economic value, natural capital, Small Island Developing States

1. Introduction

Mainstreaming natural capital requires both biophysical quantification and socioeconomic and political contextualisation of assigned value (Daily et al., 2011; Costanza et al., 2017). However, the value of natural capital for provision of ecosystem services has not been consistently translated into national-level decision-making (Guerry et al., 2015), in part due to weak links between policy and ecosystem services science (Weichselgartner and Kasperson, 2010; Perrings et al., 2011; Waite et al., 2015) and also the inconsistent quality of this science (Seppelt et al., 2011). Changing this status-quo demands reflection on current progress in ecosystem services research, through the lens of policy-making (Rosenthal et al., 2015). Such a review of current progress in understanding of ecosystem services strengthens the effectiveness of this scientific foundation (Tallis et al., 2012; Balvanera et al., 2017), enabling the identification of knowledge gaps and aiding in the development of a policy-relevant sensu (Rosenthal et al., 2015) approach to conservation of these services.

Tropical dry forests (TDFs) are among the most globally threatened ecosystems (Murphy and Lugo, 1986; Sánchez-Azofeifa and Portillo-Quintero, 2011; Sunderland et al., 2015; Banda et al., 2016) and remain underrepresented in terms of both research and protection (Sánchez-Azofeifa et al., 2005b; Miles et al., 2006; Sunderland et al., 2015). TDFs provide diverse ecosystem services, including carbon sequestration, water regulation, and erosion control (Maass et al., 2005; Balvanera et al., 2011; Portillo-Quintero et al., 2015; Calvo-Rodriguez et al., 2017) as well as the provision of food, fuel and tourism opportunities (Dunkley, 1992; van Beukering et al., 2014; Peh et al., 2015). While ecosystem services of TDF are increasingly being studied, individual studies are often local or regional in scale (Maass et al., 2005; Calvo-Rodriguez et al., 2017; Quijas et al., 2019), leaving large gaps in our knowledge at a national level (Quijas et al., 2019). Indeed, large-scale patterns in ecosystem services do not always scale to regional or local processes (Malinga et al., 2015). This is of concern, given the wide variation in TDF composition, structure and functioning and the vastly divergent response to anthropogenic and natural disturbance across its distribution (Pulla et al., 2015; Banda et al., 2016).

More than half of all TDFs are found in the Neotropics, with over 9% of these TDFs found in the insular Caribbean (Portillo-Quintero and Sánchez-Azofeifa, 2010); the Caribbean covers 0.5% of total Neotropical land area, thus makes a disproportionate contribution to TDF distribution. Despite this limited landmass, the Caribbean's native forests hosts 2.5% of the world's endemic plants (Myers, 2001) and is a key biodiversity hotspot (Sloan et al., 2014). On these small tropical islands, topography and geomorphology influences their climate and in turn, the distribution of forest formations (Lugo et al., 1981). Dry forests in the insular Caribbean are floristically and structurally distinct from those of continental systems, including characteristics such as high endemism and shorter stature (Murphy and Lugo, 1995; Banda et al., 2016). In addition, this region's TDFs includes unique transition zones between continental, West Indian, endemic and pan-tropical/Caribbean floristic elements (Oatham and Boodram, 2006a) and unlike the mainland, species richness and endemism in Antillean TDFs is at least equal to, if not higher than moist forest (Gentry, 1992; Banda et al., 2016). Yet, these unique TDFs are often overlooked in global studies of forest ecosystems (e.g. Dexter et al., 2015) and further, Caribbean terrestrial ecosystem services remain poorly documented (Calvo-Rodriguez et al., 2017).

As Small Island Developing States (SIDS), the Caribbean islands have comparatively small landmasses, high concentration of human populations and agriculture in lowland coastal areas where TDFs occur (Portillo-Quintero and Sánchez-Azofeifa, 2010). Additionally these SIDS display a high susceptibility to invasive alien species (IAS) (Lugo et al., 2012) and economic reliance on tourism (Teelucksingh et al., 2013) and forest products (Wilkie et al., 2002). The unique characteristics of islands demands particular attention in relation to the management of ecosystem services (Balzan et al., 2018). Across the Caribbean, environmental management is hindered by complex land tenure due to historical legacy, weak governance and cultural drivers and in many islands, the lowland areas are dominated by private land ownership (Griffith-Charles, 2010). This means that both agriculture and tourism development encroach on the low-lying dry forests (Walters, 2016; Mycoo et al., 2017) and with these losses, the degradation of ecosystem services. These patterns of threat and degradation have meant that the Caribbean has lost 66% of its original TDF, with over 80% of the remaining TDFs in the region highly fragmented (Portillo-Quintero and

Sánchez-Azofeifa, 2010). These insular drivers of anthropogenic land cover change differ in relative importance when compared with continental TDFs, with conversion of TDFs for tourism and invasion by exotic species, being of particular importance for insular Caribbean TDFs (Sánchez-Azofeifa and Portillo-Quintero, 2011). Yet across the region, socio-economic reliance on intact TDF habitats is high and local communities place substantial value on these forests (e.g. van Beukering and Wolfs, 2012), highlighting a potential disconnect between perceptions of value and realised land use.

There is growing interest in the benefits of environmental valuation in the Caribbean (e.g. TEEB Caribbean Netherlands, 2014; Girvan, 2015). The Caribbean is the third most populated of all the biodiversity hotspots, with an average human population density of over 170 km^{-2}, which in many islands continues to grow (Williams, 2013). Thus, it is to the governments' advantage to harness the islands' natural capital in their national accounting, to benefit this social capital. However, as elsewhere, this interest has not widely translated into decision-making and better protection for natural environments (Waite et al., 2015). Policy makers are challenged to resolve the conflict between protecting natural habitat and advancing economic development of their growing populations, complicated by patterns in land tenure that are the source of much uncertainty and conflict on the islands (Nelson, 2018). Valuing ecosystem services in the Caribbean therefore demands specific attention, given the complex socio-cultural, economic and political issues surrounding conservation decision-making in this biodiversity hotspot.

Importantly, the continuing degradation of forests and increasing threat of climate change to Caribbean SIDS (Nurse et al., 2014) and, the gap in policy analysis identified for Caribbean TDFs (Blackie et al., 2014), presents an urgent need for an assessment of current understanding of TDF ecosystem services, to inform decision-making. Here, we present a systematic review of the literature on TDF ecosystem services in the Caribbean SIDS biodiversity hotspot. Specifically, we reviewed the literature in order to (1) evaluate the current state of ecosystem service research for Caribbean TDF, (2) assess geographical and methodological patterns in this research and (3) identify knowledge gaps. We used these results to inform a discussion of the opportunities for bridging these gaps in knowledge and making these findings more relevant to policy practitioners.

2. Methods

2.1. Definitions

Historically, the definition of TDFs has been highly variable (Murphy and Lugo, 1995; Miles et al., 2006; Portillo-Quintero and Sánchez-Azofeifa, 2010; Sunderland et al., 2015), however, pronounced rainfall seasonality underpins all these definitions. Specifically, TDFs are defined by a distinct dry period lasting two to eight months (Murphy and Lugo, 1986). No systematic, detailed vegetation classification system currently covers the entirety of the insular Caribbean, since many do not provide the resolution required to be useful at a local scale (Miles et al., 2006). Here, we follow Miles et al. (2006) and define Caribbean TDFs as insular Caribbean forests with greater than 40% tree cover, and which fall within Olson et al.'s (2001) tropical and subtropical dry broad-leaved forest biome. This definitional approach allows for comparison of TDFs within and outside the region, given the wide usage of Olson et al. (2001) and the FAO definition of closed forests (FAO, 2001; Miles et al., 2006). We define ecosystem services categories according to the Millennium Ecosystem Assessment (MEA) (Alcamo and et al., 2003) and include all four categories, supporting, regulating, provisioning, and cultural, in this review (see Table S1 for definitions). Here, the insular Caribbean was defined as the 13 independent states and 15 dependent territories within the Caribbean Sea, including the Bahamas and Trinidad and Tobago (Fig. S1).

2.2. Systematic Review

The review methodology was guided by the Guidelines for Systematic Review and Evidence Synthesis in Environmental Management (Collaboration for Environmental Evidence, 2013). This systematic review was defined as a specified search methodology that included at least two databases, which identified and reviewed all publications that addressed the study aims. Boolean searches relevant to each question, were conducted of literature archived over the period 1997 to 2016, in ISI Web of Knowledge for combinations of the phrases "Caribbean", "dry forest", "ecosystem", "ecosystem services". A search was also performed using google.com, scholar.google.com and google.books.com with the first 100 pdfs or word documents examined for their inclusion suitability. In addition, grey literature databases were searched since this is an important source of data omitted from previous reviews of ES in the region (Calvo-Rodriguez et al., 2017). These databases included Treesearch, the US Forest Service Research Publications website, the Food and Agriculture Organisation (FAO) Document Repository, the United Nations Convention to Combat Desertification (UNCCD) documents centre and the Regional Clearinghouse Database of the Caribbean Community Climate Change Centre (CCCCC). The above search terms were used to search these databases, or a subset of the terms where appropriate, such as when Boolean operators were not accepted. Additional literature was also identified through in-text citations of search results, and subsequently sourced wherever possible. For study feasibility, searches were only performed in English. While we recognise that our review cannot be considered exhaustive, we consider that it represents significant coverage of the available literature, given that 64% of the 28 independent states and dependent territories in the insular Caribbean have English as an official language and much research originating from non-English-speaking islands is published in English.

We selected for inclusion in the review only the studies that:

- Focused on regional, local or national TDF in the insular Caribbean.
- Used the term 'ecosystem services' explicitly or, alternatively, described at least one component of supporting, regulating, provisioning or cultural ecosystem services in tropical dry forest.
- Presented a quantitative or qualitative assessment of a given ecosystem service component
- Had a full text available in English

Studies were then classified according to the following features:

- Publication type: "Primary research" were those papers published in peer-reviewed journals and reported original data or results from experiments, observations or models. "Grey literature" included technical reports, book chapters and unpublished reports.

- Spatial scale of each study: ‘local’ (relating to a restricted number of study sites within a country), ‘national’ (addressing issues at a national scale), ‘regional’ (examining patterns across the Caribbean).
- Type of analysis: predominately qualitative or quantitative.
- Study perspective: predominantly biophysical processes, economic, or socio-cultural.
- Ecosystem service category and subcategory (according to the MEA framework) (see Table S1 for definitions).
- Classification of ecosystem service component: ‘supply’ (potential to generate a service), ‘delivery’ (the amount/rate of use and access to service), ‘wellbeing’ (change in human wellbeing due to provision of service) and ‘value’ (monetary or non-monetary value of service), following the framework of Balvanera et al. (2017).

One reviewer conducted the search of electronic databases, recording the number of citations for each search. Articles were initially viewed by one reviewer, assigning them to all questions they addressed or, excluding them from further analysis if they did not meet the inclusion criteria, on review of the abstract or summary. Two reviewers examined a 20% proportion of studies to check corroborate study inclusion. Descriptive statistics were used to determine the number of studies for each category for the variables identified in the search protocol. Temporal change in research output was determined using linear regression for the publication date of all studies. All analyses were conducted in the R software environment (R Core Team, 2016).

3. Results

Of the results identified from all searches (n=186, removing all repetitions across databases), 37 qualified as addressing the three study aims (see Table 1 for examples of the included studies and supplementary material for a full list of these studies), with a lack of subject relevance the most common reason for rejection (53.40%) (Fig. 1). There was no temporal increase over time in the number of studies published (p = 0.06, Fig. S2).

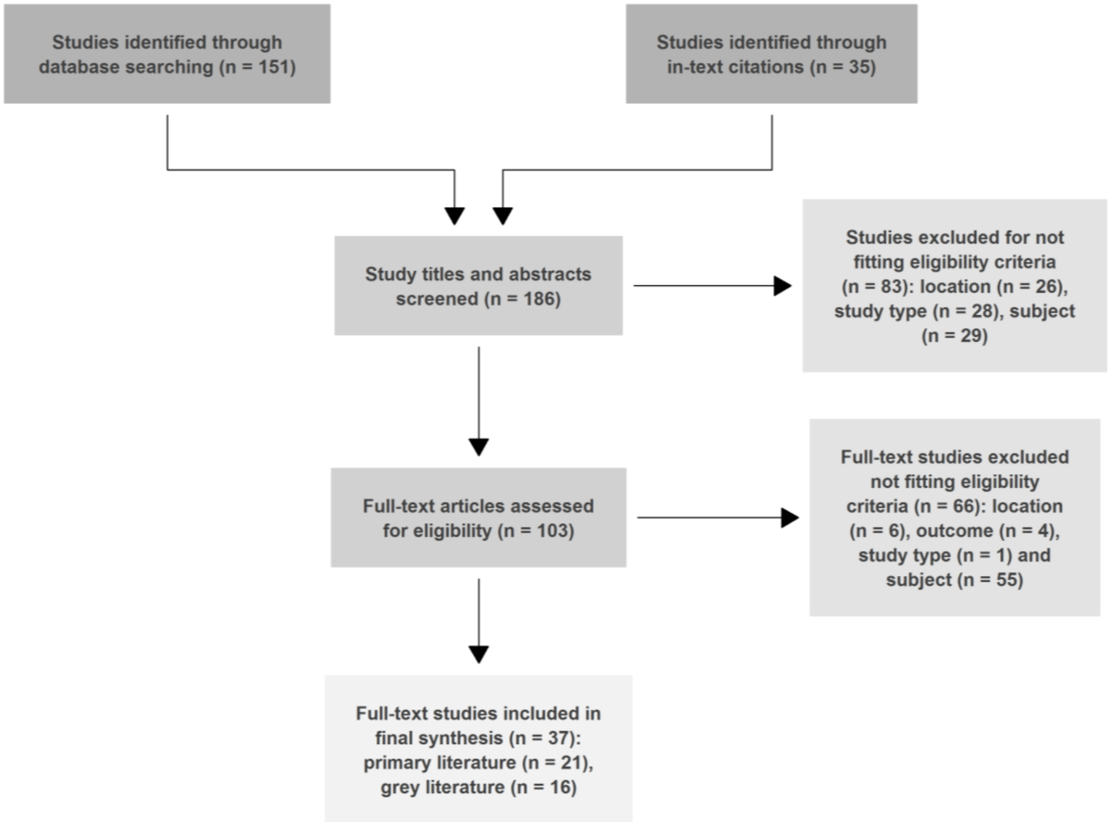

Figure 1. Flow diagram describing the results of the systematic review search strategy.

The majority of studies came from primary literature (56.76%), although the proportion varied across ecosystem service categories, with cultural services having the highest number of grey literature (Fig. 2A). All included studies were predominantly quantitative in their analysis type, and no qualitative studies were identified in the review. Supporting services studies comprised the majority of results (31.14%, Fig. 2A), with most studies addressing just one category and only two studies reporting on all ecosystem service categories (Fig. 2B). Most studies were local (40.54%) or national (45.95%) in focus. Local- or nationally-focused studies originated from nine countries or dependent territories (Fig. 3A), with Puerto Rico having the total largest number of these studies (34.38%, n=11, see Table 1 for examples). When examining this pattern by category, Puerto Rico remained dominant for supporting services (Fig. 3A), but Bonaire was a focus for cultural services (Fig. 3A, see Table 1 for examples). The average number of ecosystem service subcategories across all studies was 2.67 (95%CI 1.59- 5.69), with Montserrat and Bonaire addressing the highest number of subcategories (Fig. 3B).

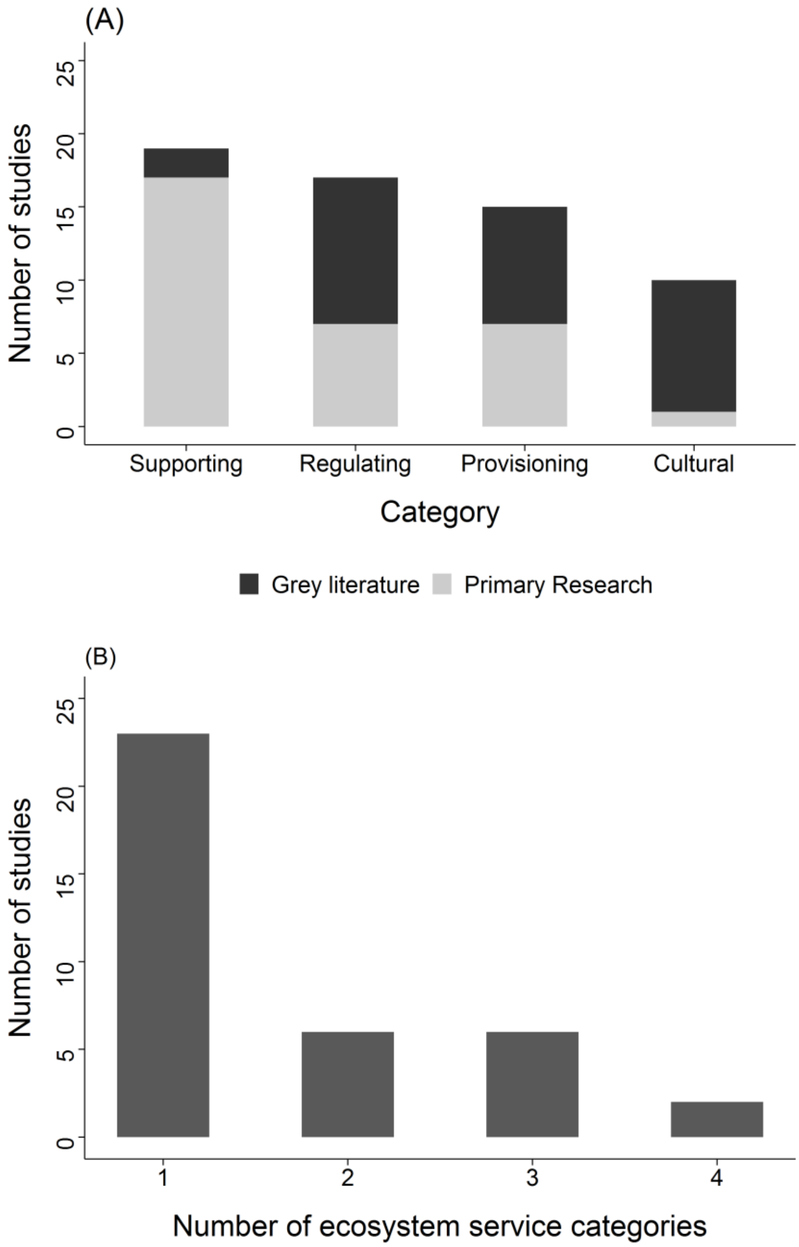

Figure 2. Results of the systematic review for (A) each ecosystem service category by publication type and (B) the number of ecosystem service categories described in each study.

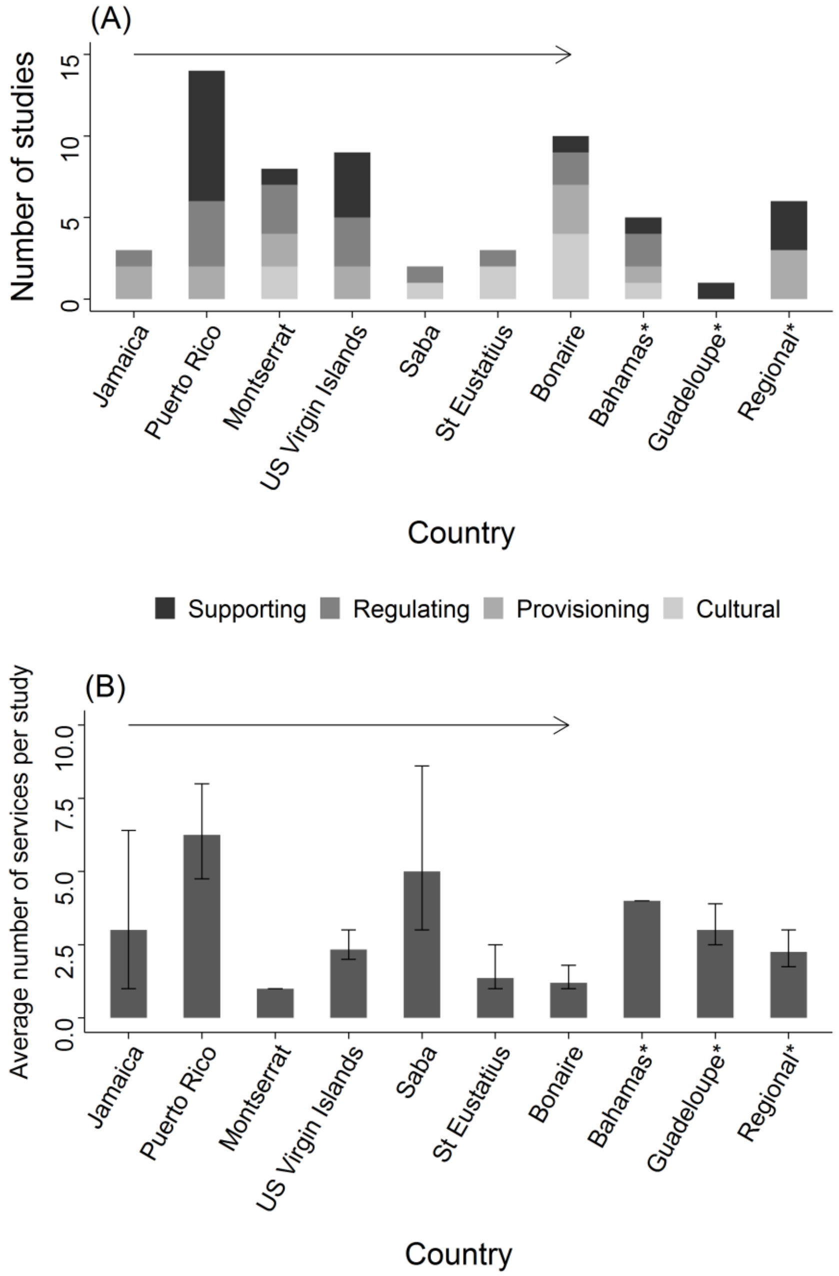

Figure 3. Per-country studies of TDF ecosystem services identified from the systematic review, showing (A) the number of studies per ecosystem service category and (B) the average number of ecosystem service components per study (within and across the four categories). Error bars indicate 95% confidence intervals and horizontal arrows indicate increasing proportion of TDF cover per country (see Table S2 for details); *no estimate of TDF cover.

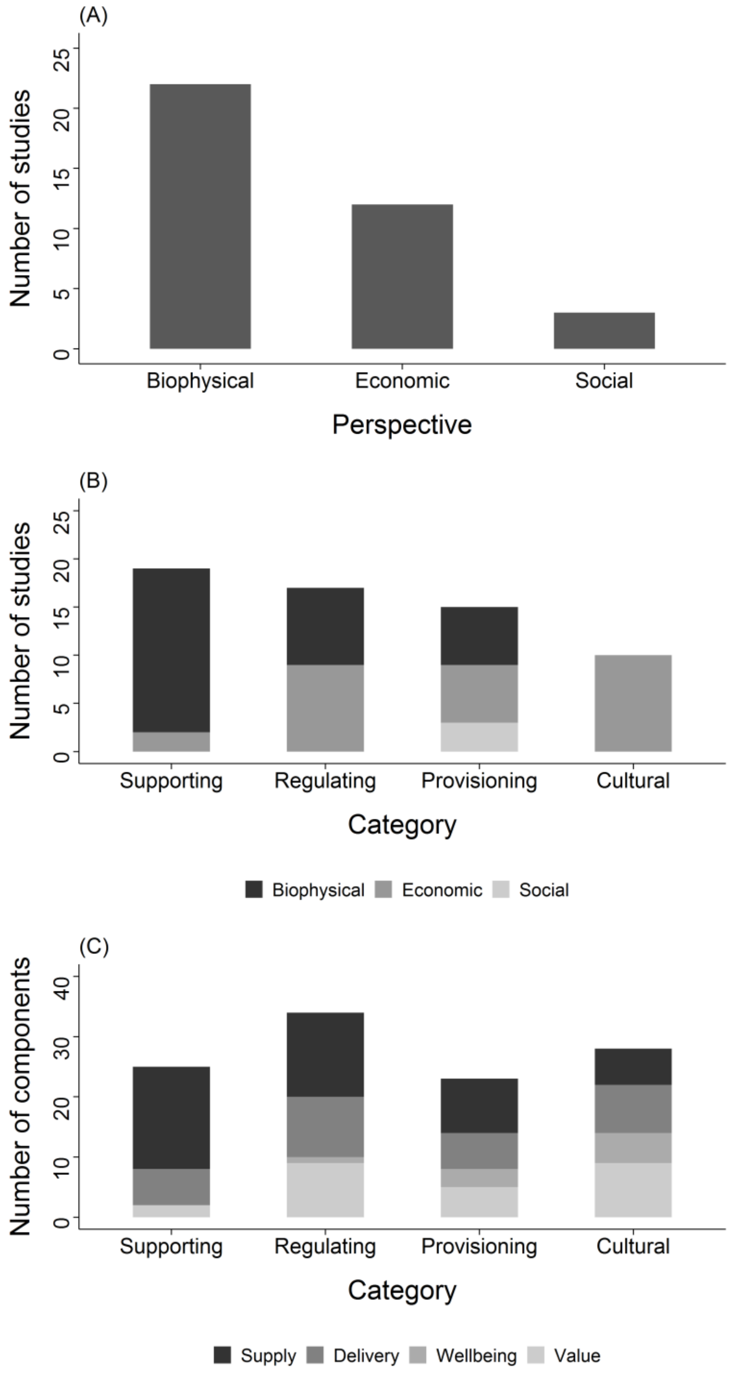

Figure 4. Results of the systematic review showing (A) the study perspective taken across all publications (B) the study perspective for each ecosystem service category and (C) the classification of ecosystem service component by ecosystem service category.

Most studies were predominately biophysical in nature (59.46%), with socio-cultural perspectives being the least often presented in the literature (Fig. 4A, B). Supporting and regulating studies had the highest proportion and number of biophysical assessments (Fig. 4B), while the proportion of studies with an economic perspective was highest in the cultural services category (Fig. 4B). In all categories except for cultural services, the supply classification measurement was predominant, being highest for the supporting services (Fig. 4C). Wellbeing components were the least quantified component across all ecosystem service categories (Fig 4C). Primary production (predominately composed of biomass estimates) and climate regulation subcategories were the most studied supporting and regulating services, respectively (Fig. 5A, B, Table 1). Materials and fuel were most the most commonly studied provisioning service (Fig. 5A), while cultural studies had a predominately tourism and recreation focus (Fig. 5C, D, Table 1).

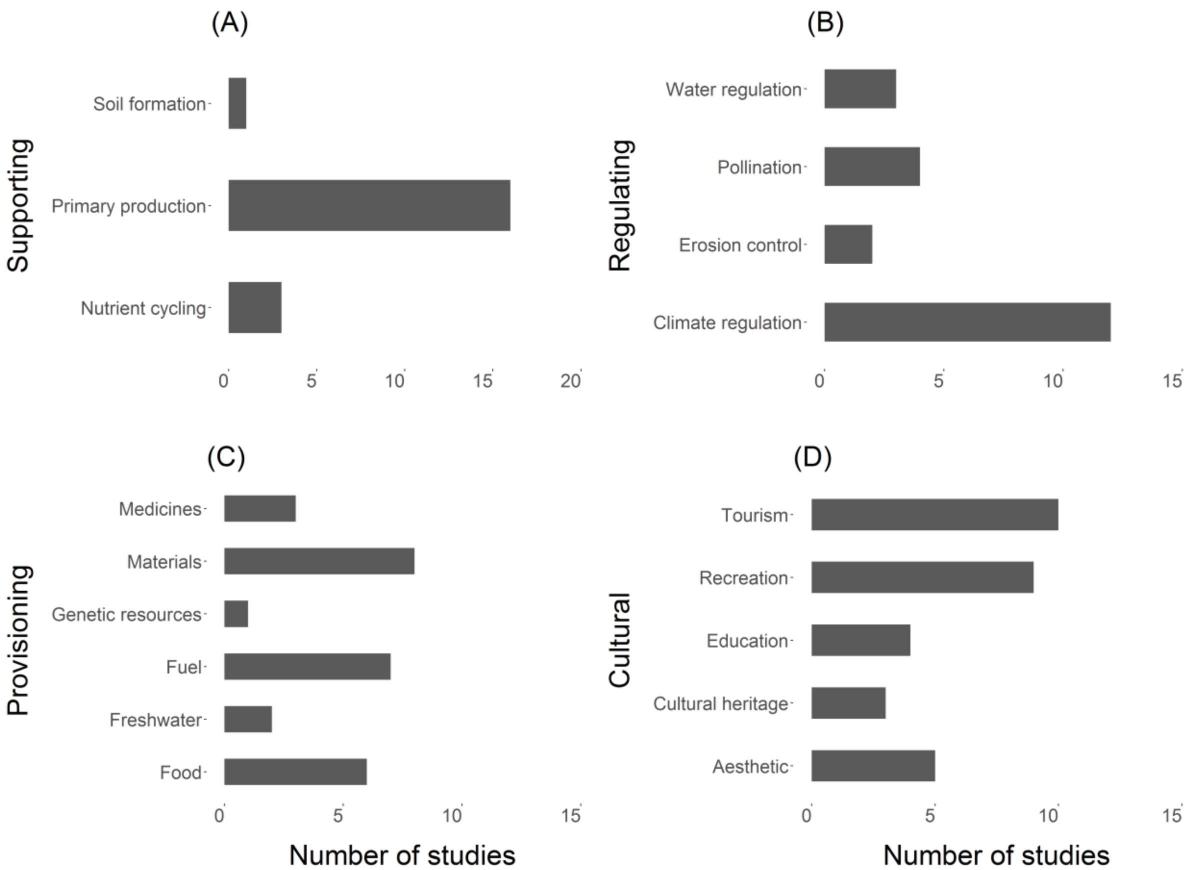

Figure 5. The major subcategories of ecosystem service categories covered in the literature review; (A) supporting services, (B) regulating services, (C) provisioning services and (D) cultural services.

Table 1. Examples of ecosystem services of Caribbean TDF based on the results of the systematic review. See Table S2 for details about the sovereignty and TDF coverage of the islands.

Service	Examples from Caribbean TDF	Island	Reference
Supporting			
Soil formation	Soil bulk density 0.4 g/cm^3 mature TDF	Puerto Rico	(Colón and Lugo, 2006)
Nutrient cycling	Dead wood a temporary sink for atmospheric carbon, source of soil organic matter, substrate for nitrogen fixation	Puerto Rico	(Torres and González, 2005)
Primary production	5.3-9.8 Mg ha^{-1} per year of primary productivity in Guanica TDF	Puerto Rico	(Clark et al., 2001)
	41.74 Mg ha^{-1} woody biomass in TDF (> 2.5cm DBH)	Puerto Rico	(Brandeis et al., 2007)
	29 Mg ha^{-1}` woody biomass in TDF (> 2.5cm DBH)	Mona Island, Puerto Rico	(Brandeis et al., 2007)
	47.65 Mg ha^{-1} woody biomass in TDF (> 2.5cm DBH)	US Virgin Islands	(Brandeis and Oswalt, 2007)
Regulating			
Climate regulation and related services	737,000 tons carbon stored in TDF	US Virgin Islands	(Brandeis and Turner, 2009)
	49.66 (Mt C) carbon stored in forest (approx. 17% TDF) (US$925.41 million).	Puerto Rico	(Smith, 2007)
	Dead wood and litter comprised average of 20% of total carbon stocks in moist and dry life zones	U.S. Virgin Islands	(Oswalt et al., 2008)
	621,000 tons yr^{-1} carbon (EC$38,454 annually) in Centre Hills (9% land cover is TDF)	Montserrat	(van Beukering et al., 2014)

Service	Examples from Caribbean TDF	Island	Reference
	Value of carbon sequestration of main ecosystems (including TDF) estimated at $290,000 annually; 115,927 tons yr^{-1} carbon stored in TDF; contribution of TDF >80% of all ecosystems;	Bonaire	(van Beukering and Wolfs, 2012)
	Cockpit County (approx. 10% TDF) carbon sequestration US$10,425,092 annually	Jamaica	(Edwards, 2011)
	27,000 tons yr^{-1} carbon stored in TDF (US $376,740 annually)	Saba	(Tieskens et al., 2014b)
	19,000 tons yr^{-1} of carbon stored in TDF (US $261,979 annually)	St Eustatius	(Tieskens et al., 2014b)
	Percent concentration of carbon 45.7 ± 1.2, nitrogen 2.3 ± 0.3 and carbon: nitrogen ratio 20.7 ± 2.5 in *Cecropia scheberiana*	Puerto Rico	(González and Seastedt, 2001)
	High percentage of carbon (52.4 ± 4.5) and low nitrogen (1.4 ± 0.5) in 53 TDF species; high carbon: nitrogen ratio 48 ± 18 may be explained by N limitation and high % carbon.	Mona Island, Puerto Rico	(Medina et al., 2014)
Water regulation and related services	Estimate of changes in spring water yield as a result of deforestation: 75% loss under complete deforestation scenario	Montserrat	(van Beukering et al., 2014)
Pollination	Total value of pollination and seed dispersal in TDF estimated at US$17,000,000.	Bonaire	(Cortes, 2012)
Provisioning			
Fuel	48% of TDF use in the Hellshire Hills and 51% in Portland Ridge related to charcoal and fuelwood use	Jamaica	(C-CAMF, 2013a, b)
	5% population collect charcoal/firewood from Centre Hills (including TDF)	Montserrat	(van Beukering et al., 2014)
Food	15% population collect fruit once or more annually from Centre Hills (including 9% TDF).	Montserrat	(van Beukering et al., 2014)

Service	Examples from Caribbean TDF	Island	Reference
	Total annual profit from hunting wild meat in the Centre Hills (9% TDF) US$205,000	Montserrat	(Peh et al., 2015)
Materials	Red (*Cedrela* sp.) and white cedar (*Tabebuia* sp.) for furniture production (< 2% population) from Centre Hills (9% land cover is TDF), $EC14.95 and $EC15.00 per linear foot, respectively.	Montserrat	(van Beukering et al., 2014)
	2% population collect craft materials, e.g. seeds, beads, wood, bark, leaves, flowers (including TDF)	Montserrat	(van Beukering et al., 2014)
Freshwater	100 million gallons per month from Centre Hills (9% TDF), 80% for public supply; 88 million gallons sold annually (EC$2,656,000).	Montserrat	(van Beukering et al., 2014)
Genetic resources	Low gene flow and genetic diversity in bat-pollinated *Hymenaea courbaril;* high gene flow and diversity in fragmented *Bursera simaruba* populations and the insect-pollinated non-native *Albizia lebbek.*	Puerto Rico	(Dunphy, 2003)
Natural medicines	Large proportion of population regularly collect and use medicinal plants (from all ecosystems including TDF, worth $344,394 annually)	Bonaire	(van Beukering and Wolfs, 2012)
	7% population collect medicinal plants (including TDF)	Montserrat	(van Beukering et al., 2014)
Cultural			
Recreation	Hunting (8%), Hiking, camping, wildlife watching, picnicking in Centre Hills (including 9% TDF)	Montserrat	(van Beukering et al., 2014; Peh et al., 2015)
	Recreational and cultural value of forested (TDF) habitat (US$30,825 annually)	Saba	(Tieskens et al., 2014a)
	Hiking, natural landscapes, including TDF	St Eustatius	(Tieskens et al., 2014b)
	Wildlife viewing, natural environment, including TDF (EC$20-25 million annually).	Montserrat	(van Beukering et al., 2014)

Service	Examples from Caribbean TDF	Island	Reference
	Hiking in forested (TDF) habitat (US$3,233,386 annually)	Saba	(Tieskens et al., 2014a)
Tourism	Total value of terrestrial tourism for island, US$1,231,309.84 annually	St Eustatius	(Tieskens et al., 2014b)
	TEEB models suggest US$15000 could be generated annually from birdwatching, including in TDF	Bonaire	(Cortes, 2012)
	Total annual expenditure US$419,000 from International tourists to Centre Hills (including 9% TDF)	Montserrat	(van Beukering et al., 2014; Peh et al., 2015)
Aesthetic, spiritual, inspirational	Value of artistic inspiration of all ecosystems (including TDF) estimated at $460,000 annually	Bonaire	(van Beukering and Wolfs, 2012)
	Local residents were willing to pay US$9.07 per month for high quality terrestrial habitat (including TDF)	Bonaire	(Lacle et al., 2012)
Cultural heritage	Local value for culture and recreation US$41,315 (including TDF)	St Eustatius	(Tieskens et al., 2014b)
Educational	Education impact of natural resources on Andros Island, Bahamas, estimated at US $2,800 (209)	Bahamas	(Hargreaves-Allen, 2010)
	Total value (including TDF) for scientific research estimated US$1,240,000 - US$1,485,000	Bonaire	(van Beukering and Wolfs, 2012)

4. Discussion

Caribbean TDFs are recognised as being significantly under-researched compared to TDFs across Latin America (Blackie et al., 2014). Our results are consistent with this observation, identifying substantial knowledge and geographic gaps in the evidence for ecosystem services in Caribbean TDFs. Here, we discuss the findings from this systematic review, highlighting the status of our current understanding and important knowledge gaps, relevant to mainstreaming ecosystem services in the Caribbean (Bizikova et al., 2018), and discuss the potential research opportunities that can improve the relevance of these data to ecosystem services policy in the region.

4.1. Patterns in research effort

In contrast to much of the wider ecosystem service literature (Liquete et al., 2013; Luederitz et al., 2015; Cruz-Garcia et al., 2017; Balzan et al., 2018), there was no significant temporal increase in research of Caribbean TDF ecosystem services. Although this pattern was in part due to the small sample size of eligible results, it may also reflect the generally low global research effort for TDF systems compared to other forest systems. Nearly half of the search results were published in the grey literature, highlighting the importance of including such information in knowledge assessments. Such publications are vital for bridging the researcher-practitioner gap, since peer-reviewed literature is often unobtainable by practitioners or often asks the wrong questions (Gossa et al., 2015). Yet, many reviews of ecosystem services omit these valuable data (e.g. Liquete et al., 2013; Luederitz et al., 2015; Malinga et al., 2015; Calvo-Rodriguez et al., 2017). As is also established for Caribbean marine ecosystem services (Schuhmann and Mahon, 2015), our results demonstrate that their inclusion is justified to avoid a mis-representation of the current state of knowledge.

The larger islands (Cuba, Hispaniola, Puerto Rico and Jamaica) have the greatest extent of TDFs (Portillo-Quintero and Sánchez-Azofeifa, 2010), but not necessarily the greatest relative proportion of TDF forest cover (Table S1). The published English-language literature on ecosystem services in these Greater Antillean TDFs reflects, in part, this distribution. Yet, in general, there was low research effort in those islands with proportionally high TDF forest cover, with Puerto Rico having disproportionately high research effort compared to coverage of TDF, indicating that the amount of TDF per se, is not a driver of research. Unsurprisingly, many of the countries represented in this review are overseas departments or dependencies (e.g. Puerto Rico, Caribbean Netherlands) with external support (such as the International Institute for Tropical Forestry of the US Forest Service), host large universities (e.g. Universidad de Puerto Rico, University of the West Indies-Mona Jamaica), and/or large remaining tracts of TDFs (e.g. Jamaica). Extending the language scope of this review would provide further insight into these patterns, since restricting this review to English-speaking publications undoubtedly led to an underrepresentation of research effort, although it should be noted that four of the islands represented in the review are non-English speaking (Bonaire, Guadeloupe, Saba, St Eustatius).

In this review, as found elsewhere (Cruz-Garcia et al., 2017), studies tended to focus on two or less ecosystem service categories. This narrow focus is repeated when examining the number of ecosystem components per study, which is also observed more widely in the study of ecosystem services (Seppelt et al., 2011; Liquete et al., 2013; Weitzman, 2019). Examining ecosystem services in isolation runs the risk of failing to understand processes such as cascading effects, feedbacks, trade-offs and interactions between services. This is particularly true for ecosystem services on islands, given their unique ecological characteristics and socio-economic challenges (Balzan et al., 2018). The importance of understanding this aspect of ecosystem services is increasingly recognised for achieving effective translation into decision-making, such as in the context of biodiversity loss and climate change (Seppelt et al., 2011; Evers et al., 2018). Such mainstreaming of ecosystem service data into policy-relevant information, requires an explicit consideration of the need for integration of policy-makers in the process of study objective formulation and data generation (Rosenthal et al., 2015; Bizikova et al., 2018).

Studies of supporting, regulating and provisioning ecosystem services often have a biophysical focus (Martínez-Harms and Balvanera, 2012; Liquete et al., 2013; Evers et al., 2018), reflecting that these measures are typically components of ecologically rather than economically focused studies (Czúcz et al., 2018). This pattern was also observed for Caribbean TDF. The high proportion of studies focusing on supporting, regulating and provisioning services is consistent with other studies (Martínez-Harms and Balvanera, 2012;

Luederitz et al., 2015; Malinga et al., 2015; Calvo-Rodriguez et al., 2017). Here, estimates of biomass, a fundamental measurement of forest inventories (e.g. Brandeis and Turner, 2009) were dominant. These data in particular, demonstrate the value of long-term monitoring programmes such as those conducted by the International Institute for Tropical Forestry in Puerto Rico. Such biophysical data are however, important foundations for translating ecosystem functioning into measures of ecosystem services (Seppelt et al., 2011), thus providing the basis for economic accounting.

Quantitative estimates of all ecosystem service categories were dominant in this review. Although as is found more widely (Liquete et al., 2013; Luederitz et al., 2015; Malinga et al., 2015), the absolute number of assessments of cultural ecosystem services was low, this category had the highest proportion of studies taking an economic perspective. Such market-based cultural values are comparatively easy to measure, using the commonly applied contingent valuation and cost-based approaches (De Groot et al., 2002; Brooks et al., 2014). This patterns is also observed for Caribbean marine systems (Schuhmann and Mahon, 2015). However, the intangibility of many non-use cultural services, such as aesthetics, means that they can be a challenge to quantify economically and to date, many cultural valuations have focused on tourism and recreation services (Seppelt et al., 2011; Liquete et al., 2013; Schuhmann and Mahon, 2015). This review echoes these findings.

To date, most ecosystem service research focuses on quantifying the supply element of classifying ecosystem service components, since this is often the most easily quantified (Tallis et al., 2012; Balvanera et al., 2017). Our results illustrate a similar pattern, with the quantification of supply and delivery of ecosystem service provision comprising the majority of all categories, consistent with the mainly biophysical focus of studies. As expected, wellbeing was rarely quantified in our review, given the difficulties in understanding and demonstrating change to human wellbeing (Balvanera et al., 2017; Cruz-Garcia et al., 2017). Ecosystem services of TDF more widely have not yet been fully explored in the context of this conceptual framework of supply, delivery and benefit (Tallis et al., 2012; Balvanera et al., 2017). Applying such a framework in this review is a useful starting point for evaluating the breadth and quality of existing data Caribbean TDF ecosystem services, leading to improved understanding of these systems.

4.2. Current understanding of Caribbean TDFs ecosystem services

In the Caribbean, where water demand often exceeds availability (ECLAC, 2011), water regulating services are arguably among the most important ecosystem service provided by TDFs (Portillo-Quintero et al., 2015). For example, the Centre Hills Reserve in Montserrat, of which TDF comprises 9%, produces 100 million gallons of water annually (van Beukering et al., 2014), although the study does not distinguish between forest types. Given the importance of water to TDF structure and functioning (Murphy and Lugo, 1995), as well as to humans, the low frequency of water-related services publications in the literature is of concern, especially since water processes in TDF are highly sensitive to temporal and spatial water availability (Balvanera et al., 2011). This poor understanding of water ecosystem services was also observed for TDF more widely (Calvo-Rodriguez et al., 2017; Quijas et al., 2019) and is consistent with a broader lack of understanding of the hydrology in these systems (Farrick and Branfireun, 2013).

As illustrated in this review, carbon-related supporting, regulating and provision services are the most widely estimated ecosystem services for Caribbean TDFs. These studies demonstrate the substantial carbon storage function of TDFs, most commonly measured through woody biomass. Measuring biomass is recommended for decreasing uncertainty in our understanding of climate cycles and improving estimates of terrestrial carbon stocks and carbon accounting and, is also an important indicator of other ecosystem services (Houghton et al., 2009; Le Toan et al., 2011). Although woody biomass is generally lower in TDFs than moist forest (Brandeis and Turner, 2009), in many of the drier islands, TDF is the dominant forest type. Based on this review, increasing the existing low coverage of TDF in protected areas in the Caribbean (Oatham and Boodram, 2006b) could make a substantial contribution to ecosystem service provision for these islands. In this context, efforts should be made to translate the mostly biophysical estimates of woody biomass into the economic value of this service.

TDFs provide multiple provisioning services in the Caribbean, including energy, food, and materials, such as non-timber forest products (NTFPs). For example, charcoal from TDF remains an important source of fuel in many islands, including Jamaica and Montserrat (C-

CAMF, 2013b; van Beukering et al., 2014). Although production forestry has declined in the Caribbean (John, 2005), NTFP use including medicines and crafts from TDF is widespread (e.g. FAO, 2010; van Beukering et al., 2014), as highlighted in this review. However, across the Neotropics the provisioning services of TDFs are negatively impacted by habitat alteration (Balvanera et al., 2011; Portillo-Quintero et al., 2015), such as due to extreme weather or anthropogenic impacts. While data on habitat degradation or reduction are not widely or reliably available for the insular Caribbean, the findings from this review suggest that a reduction in ecosystem functioning of Caribbean TDF could have a tangible economic impact for local communities in the region.

Recreation, tourism and aesthetics are consistently demonstrated as valuable cultural uses of Caribbean TDF ecosystems in this review. Local communities value intact TDF habitat, with residents of Bonaire willing to pay nearly US$10 per month for terrestrial habitat to remain in good condition (Lacle et al., 2012). The reliance of many countries on tourism also means that TDF habitat can be worth up to US$3 million annually on individual islands for hiking and birdwatching (Cortes, 2012; Tieskens et al., 2014a; Tieskens et al., 2014b). However, existing knowledge is patchy across the region, with cultural assessments having the smallest number and geographic range of studies in this review. Ironically, in many islands TDF habitat is viewed as low value scrub and is often converted to agriculture (Wilkie et al., 2002; Peters, 2011), despite the potential value for tourism. This possible disparity in perception between culturally important and valueless TDF demands further examination for the Caribbean.

4.3. Gaps in knowledge and identifying constraints

We found substantial knowledge gaps of ecosystem services for Caribbean TDF. For example, our study found limited quantification of water provisioning by TDFs in the Caribbean, while genetic studies were almost non-existent and as found for other Neotropical TDFs (Calvo-Rodriguez et al., 2017; Quijas et al., 2019), there were no studies on air-related services. With many Caribbean TDF now considered novel communities due to IAS species in these systems (Lugo et al., 2006), a further absence from this review was the quantification of the relative contribution of native and introduced species to ecosystem service provision and, the relative resiliency of native communities to resist invasive species colonisation and establishment. These gaps indicate a considerable limitation in our understanding of the response of TDF ecosystem services to environmental change, such as climate change (see Nelson et al., 2018), as well as our ability to assess the total economic value of these systems. Much of the focus for ecosystems services of Caribbean SIDS has been on coastal, coral reef and mangrove ecosystems (e.g. see Schuhmann and Mahon, 2015 and references therein). However, research on TDF ecosystem services the insular Caribbean have been limited, unlike the rest of Latin America (e.g. Maass and Burgos, 2011; Calvo-Rodriguez et al., 2017) where work on these forests is rapidly advancing.

In the Caribbean, there are a lack of cultural valuations for TDFs, although these are notable for the Dutch dependencies (van Beukering and Wolfs, 2012; Tieskens et al., 2014b). This gap is particularly apparent in the primary literature and the failure to understand the relationship of local communities with TDF is a recognised limitation for management in the Neotropics (Sánchez-Azofeifa et al., 2005a; Blackie et al., 2014; Castillo et al., 2018). Importantly, few studies in this review quantified the human wellbeing benefits of TDF, possibly since these indicators are considered hard to measure (Balvanera et al., 2017). Participatory methods, sustainable livelihoods frameworks and policy network analysis are vital to engage stakeholders and utilise local knowledge in order to advance socio-cultural understanding (CANARI, 2016).

This review of ecosystem services provided by TDFs in the insular Caribbean, although pointing to the importance of such TDFs services, suggests that generally, the published evidence is limited in distribution and often un-replicated. In addition to the data gaps described above, shortcomings identified by this review include the paucity of the continuous long-term data on baseline ecosystem services, that is necessary to understand inter-and intra-annual environmental variability (Lindenmayer et al., 2012). A further consideration is that much of the existing literature does not clearly distinguish TDF from other forest types. This may in part reflect that forest definitions are often dictated by different management objectives, leading to a dichotomy between land management versus production forestry (Chazdon et al., 2016). These knowledge weaknesses hinder our ability to determine long-term change in TDF ecosystem services, as well as our ability to successfully influence decision-making.

Understanding gaps in knowledge requires an understanding of the underlying factors influencing research in the insular Caribbean. A major constraint of ecological research in SIDS such as the Caribbean, is lack of resources and human capacity (Kaiser-Bunbury et al., 2015). Widespread understaffing and high demands on natural resources managers limits the indigenous ability to undertake the long-term research that is required to answer vital questions about TDF systems. Increasing the capacity of natural resource managers, through training, motivation and technical support, is instrumental for future long-term forest management and research (Marcano-Vega et al., 2016). While it is crucial to advocate for capacity building, the long time-lags in developing professional level competence will lead to the lack of capacity in Caribbean management agencies remaining a persistent challenge to furthering research on TDF ecosystem services. Until increases in local capacity are realised, collaborations with foreign researchers will remain important for understanding forest systems. Yet, these researchers frequently fail to train, engage or share data with local resource managers and researchers and unless this work is subsequently published, it rarely gets into the realm of decision-makers (Kaiser-Bunbury et al., 2015). Permanent plots are often set up by foreign researchers or by international collaborations, such as by the FAO Tropical Forestry Action Programme in the 1980s, but then are infrequently re-visited or data is not used for management due to lack of manpower, resources and loss of institutional memory (Fairhead and Leach, 2002; Marcano-Vega et al., 2016). These problems exemplify the challenge of bridging conservation science and application in SIDS and emphasise the need for researchers to engage local practitioners (Kaiser-Bunbury et al., 2015). Importantly, the relevance of ecosystem services research to environmental policy hinges on the perceptions of the legitimacy of this research by policy makers (Posner et al., 2016). Such legitimacy is central to the utility of ecosystem services research, to mainstreaming of ecosystem services.

4.4. The way forward

Ultimately, a central goal of valuing ecosystem services is to facilitate mainstreaming into national policies (Guerry et al., 2015). Evidence from valuation studies that have successfully influenced decision-making in the Caribbean suggest that success stems from identification of appropriate policy questions, fully engaging stakeholders, and transparency and strategic communication (Waite et al., 2015). In the context of current ecosystem services research of Caribbean TDF, this requires adopting an approach that is focused on data gaps and policy-relevant questions that are co-constructed by stakeholders and researchers, rather than more ad-hoc approaches based on data availability and methodological ease. In this context, we make recommendations for key policy-relevant research (with examples of their policy implications) (Table 2).

Table 2. Recommendations for future policy-relevant research, based on the systematic review of Caribbean TDF ecosystem services.

Recommendation	**Knowledge gap for Caribbean TDF**	**Policy objective**	**Examples of research from Neotropical TDF**	**References**
Total Economic Valuation (TEV) of ecosystem goods and services from TDF (e.g. UNEPs TEEB and Project for Ecosystem Services (ProEcoServ) UNEP).	Quantification of the economic and wellbeing value of services (Table 1, Fig.3, Fig. 4).	Provide economic incentive for mainstreaming ecosystem services into national planning accounting systems and develop framework for engagement of stakeholders in conservation of ecosystem goods and services from TDF.	The TEEB approach as used in the Dutch Islands, is a useful participatory framework to be more widely applied in the region.	(Cortes, 2012; Tieskens et al., 2014a)
Ground and surface water conservation value of TDF (e.g. using payment for ecosystem services, PES).	Contribution of TDF to water-related ecosystem services (Table 1, Fig. 5).	To quantify TDF contribution to water-related ecosystem services and so enable PES to sustainably finance TDF management and incentivise sustainable land management practices on private lands in watersheds, where climate-driven TDF expansion may be expected later in this century	PES models already successfully demonstrated for maintaining TDF in Chaco, Argentina. Long-term study of rainfall and water run-off in TDF, Mexico	(Maass et al., 2018; Nunez-Regueiro et al., 2018)
Co-benefits of TDF ecosystem function for agricultural production (e.g. pollination, soil conservation, water supply).	The value and importance of TDF ecosystem services to agricultural	Valuation of TDF contribution to the agricultural sector leads to rationalisation of incentivisation across the agriculture, forests and protected area sectors, promoting	Resiliency of TDF soil to pasture use in Mexico.	(Ayala-Orozco et al., 2018; Zelaya et al., 2018)

	productivity (Table 1, Fig. 5).	TDF conservation and long-term stakeholder education on sustainable land management practices on agricultural landscapes around TDF	The impact of TDF fragments on pollination of Soybean, Argentina	
Valuation of NTFPs (e.g. honey, medicinal plants, building materials, game wildlife and fruits) and pharmaceutical bioprospecting of TDF species (e.g. willingness-to--pay for potentially marketable forest-derived drugs).	Quantification of local community reliance on TDF NTFPS for livelihoods and subsistence (Table 1, Fig. 4, Fig. 5).	Monetise and diversify livelihoods, goods and services from TDFs to increase their perceived and actual value to local people and improve sustainability of NTFP management.	The economic value of TDF NTFPs for indigenous communities, Mexico The use value of TDF species for medicine and food, Mexico	(Marshall et al., 2006; Maldonado et al., 2013)
Long-term monitoring of climate change impacts on ecosystem functioning and provision of ecosystem services of TDF (e.g. changes in biomass, water regulation and pollination).	Lack of long-term data on TDF ecosystem service responses to environmental change (Table 1).	Develop climate change adaptation that explicitly addresses impacts on ecosystem goods and services in national policies and promote ecosystem management approach to manage transition to future drier climates.	Long-term study of TDF species drought tolerance, Caatinga, Brazil. Water availability, ENSO and primary productivity in Costa Rica	(Santos et al., 2014; Castro et al., 2018)
Impact of invasive alien species (IAS) on ecological functioning and ecosystem services of TDF (e.g. carbon storage, soil stability, aesthetic value).	IAS are identified as a major threat to TDF, but their impact on and contribution to ecosystem services remains unquantified (Table 1).	Implementation of monitoring and control to mitigate threats of existing IAS and avoid transportation of potentially new IAS.	Litter decomposition in novel TDF communities, Puerto Rico.	(Peh et al., 2015; Lugo and Erickson, 2017)

			Economic impact of feral livestock control, Montserrat	
Genetic resources (provisioning) of native and non-native TDF species (e.g. genetic diversity, resistance to disease, adaptive capacity).	Contribution of genetic factors to TDF provisioning services and their response to environmental change (Table 1, Fig. 5).	Quantify threats to, and value of genetic diversity, ensure equitable sharing of benefits provided by TDF species.	Effects of fragmentation on genetic structure and reproductive success of TDF species, Costa Rica. Genetic diversity of TDF timber species, Costa Rica.	(Fuchs et al., 2003; Villalobos-Barrantes et al., 2015)
Health and well-being contributions of TDF (e.g. clean air and water supply, flood protection, access to TDF, livelihoods).	Knowledge gap: the role of TDF in local health and wellbeing, culture and livelihood provision (Table 1, Fig. 2-5).	Mainstream ecosystem services and explicitly link human health, environmental and agricultural policies, that promote sustainable land management.	Impact of protected areas for local communities wellbeing and livelihoods, Brazil. Human wellbeing under future management scenarios	(Maass et al., 2005; Anaya and Espírito-Santo, 2018)

5. Conclusion

This review highlights the relevance and contribution of TDFs for wider ecosystem and socio-economic functioning in the insular Caribbean. Examining our current understanding at a regional level provides a level of insight not possible from coarse-scale analyses. Here, we highlight not only the strengths of current research but also key areas for future study. Many of these gaps in knowledge reflect patterns and challenges experienced more widely in SIDS. To move beyond biophysical assessments towards meaningful valuation and successfully mainstreaming the ecosystem services of TDF into Caribbean decision-making requires a collaborative and strategic assessment approach.

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