Examining the Sustainability of Tropical Island Forests: Advances and Challenges in Measurement, Monitoring, and Reporting in the U.S. Caribbean and Pacific

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Received: 1 July 2019; Accepted: 12 October 2019; Published: 24 October 2019

Abstract: Forests across the U.S. and U.S. affiliated islands of the Caribbean and Pacific constitute rich and dynamic social-ecological systems that, while heterogeneous in many ways, share certain characteristics and trends that underscore the utility of sustainability assessments that go beyond single jurisdictional efforts. This paper summarizes a recent effort to assess the sustainability of tropical island forests of and politically affiliated with the U.S. using the Montréal Process criteria and indicator framework (MP C&I), which address ecological, social, economic, and institutional dimensions of forests. Forests cover 45 percent of the total area and more than 50 percent of each island jurisdiction, except Hawaii (36 percent). Forest cover is generally stable over much of the area in terms of recent reference conditions. The history of human occupation and land alteration is a prominent determinant of current conditions throughout the islands, which exhibit relatively high rates of threatened species in comparison to mainland counterparts and particularly where endemism is high. The islands also harbor significant areas of new or novel assemblages of native and non-native forest species, predominately on abandoned agricultural lands cleared of native forests long ago, which have been shown to contribute to the restoration of these degraded lands and provide many other ecosystem services at levels as high as and in some cases higher than native forests. Although industrial-level commercial timber harvest is small to nonexistent on most islands, socioeconomic and cultural linkages to forests are extensive but difficult to quantify. Amassing a foundation of data sufficient to address the MP C&I was challenging, in part due to the heterogeneity of the islands, island geography, and limited reporting capacities. We document significant improvements in the availability of data important for sustainability assessments in the last decade or so, especially with the extension of the U.S. Department of Agriculture Forest Service Forest Inventory and Analysis program to the islands. Likewise, we find the MP C&I to be a useful tool for organizing and presenting information important for assessing forest sustainability. Nevertheless, considerable data gaps remain in the areas of biodiversity, forest functions and processes, and socioeconomic conditions of forests, which are critical elements to track across the islands, particularly in the context of climate change and ongoing anthropogenic pressures.

Keywords: forest sustainability; forest inventory; criteria and indicators; tropical forests; Hawaii; Pacific islands; Caribbean islands
1. Introduction

More than a dozen island jurisdictions in the Caribbean and Pacific are politically affiliated with the United States, including the state of Hawaii, the territories of American Samoa, Guam, Puerto Rico, and the U.S. Virgin Islands, and the freely associated states of the Republic of the Marshall Islands, Federated States of Micronesia, Commonwealth of Northern Marianas, and Republic of Palau. These islands are rich in biological and cultural diversity, but they are faced with many challenges including reliance on imports for food and fuel security, limited supplies of fresh water, sea level rise, and increasingly unpredictable extreme weather events [1–6], some of which may be moderated or mitigated by the sustainable use and protection of forest ecosystems.

Forests span a wide range of life zones across the Caribbean and Pacific islands and harbor many rare and range-restricted or endemic species [7–9]. These forests are important socioeconomically, supporting local livelihoods and providing ecosystem services from local to global communities. Yet, they are subject to clearing and conversion to development, over-harvesting, introduction of non-native animal and plant species deemed invasive, and other anthropogenic and non-anthropogenic disturbances that have led to changes in forest cover and composition and are tied to high rates of species endangerment [1,10–13].

Understanding forest conditions and trends across ecological, economic, and social dimensions is of critical importance to sound policies and practices related to their use and conservation, and requires robust and reliable data across a broad spectrum of factors. However, consistent and comparable information on Caribbean and Pacific island forests as complex social-ecological systems is limited. Moreover, these islands often are overlooked or treated superficially in U.S. national-level forest sustainability and related analyses and reporting efforts, leaving local governments, federal partners, and other key actors with insufficient or partial information for forest-related policy- and decision-making. To address these knowledge gaps, we undertook a comprehensive sustainability assessment of ecological, economic, and social forest conditions and trends across nine Caribbean and Pacific island jurisdictions of and politically affiliated with the U.S. (Figure 1).

![Figure 1. Location of the nine island jurisdictions encompassing the study area.](image-url)
Criteria and Indicators of Forest Sustainability

Measures of forest sustainability generally encompass ecological, economic, and social components and incorporate the ideals of intra- and inter-generational equity. These components can be delineated further into their specific parts and processes through criteria, which define the essential elements against which sustainability is assessed, and indicators, which are measurable parameters that correspond to a particular criterion [14,15]. Examining forest sustainability through criteria and indicators (C&I) often involves a set of basic questions related to these component parts and processes. For instance, is forest area and structure being conserved? Are ecosystem functions and services being maintained? Is biodiversity being preserved? Are socioeconomic conditions improving? Are human institutions up to the task of sustainable forest management?

The immediate answers to these questions may indicate if and where more analysis is needed and, ultimately, where policy responses are required, which may necessitate new or increased levels of investment, cooperation, or other forms of intervention or adaptation in certain contexts, disturbance regimes, or tipping points. The answers to these questions and the associated responses also depend on the definition and assumptions associated with ‘sustainability’, which tend to evolve over time. Although there is ongoing debate at local to global levels on the definition, component parts, and bounds of ‘forest sustainability’ and the utility of associated evaluations and applications (see for example [16–19]), periodic assessments of forests through C&I permit the tracking of conditions and trends across a comprehensive set of critical forest components and processes; the incorporation of new, emerging, or previously unmonitored aspects over time; and perhaps most importantly, the identification of parts or processes that shift beyond reference or otherwise collectively-agreed desired conditions [20–22].

We utilized the Montréal Process Criteria and Indicators for the Sustainable Management of Temperate and Boreal Forests (MP C&I) as a framework for collecting, analyzing, and reporting information on the ecological, economic, and social dimensions of the islands’ forests [23]. The MP C&I is one of nine regional or forest-type frameworks developed over the past two to three decades through international initiatives to support forest sustainability measurement, monitoring, and reporting. These nine initiatives share many of the same or similar measures, integrating ecological with economic and social indicators towards a more holistic examination of forests as social-ecological systems [17,24]. While a tropics-oriented C&I framework may seem more fitting for this study, the MP C&I framework has several advantages in this particular application (in addition to the fact that most of the MP indicators are similar to those in the various other frameworks currently in use): (1) the MP C&I have been in use by twelve member countries for over twenty years and revised over time based on experience from their application, such that the current indicator set has been vetted internationally; (2) it is designed for flexible application across different countries and settings; and (3) it aligns with ongoing U.S. temperate forest sustainability assessment and reporting activities, permitting increased integration and visibility of island forest conditions and trends in future national level efforts [25].

The MP C&I are comprised of fifty-four indicators arranged under seven overarching criteria (Table 1). The first five criteria and twenty-four associated indicators address biophysical forest characteristics. The sixth criterion encompasses twenty indicators that address the social and economic aspects of forests. The seventh criterion and its ten indicators address laws, policies, and other institutional factors associated with forests and their management.

In the sections that follow, we provide an overview of the nine island jurisdictions included in this study, followed by a brief description of the methods we used for this assessment. Then, we present forest conditions and trends within and across jurisdictions organized by MP criterion. Finally, we discuss the overarching key findings from our assessment and reflect on the advances and limitations of forest sustainability assessments in tropical island settings, considering theoretical as well as practical implications.
Table 1. Montreal Process Criteria and Indicators criterion level summary.

<table>
<thead>
<tr>
<th>Criterion Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Conservation of biological diversity</td>
<td>Nine indicators describing the biophysical characteristics of forests, including forest extent, composition, diversity of flora and fauna. Conservation efforts also covered</td>
</tr>
<tr>
<td>2. Maintenance of productive capacity of forest ecosystems</td>
<td>Five indicators describing forest productive capacity, area of planted forests, and current production levels of forest outputs (timber and nontimber)</td>
</tr>
<tr>
<td>3. Maintenance of forest ecosystem health and vitality</td>
<td>Two indicators describing (1) biotic forest disturbance processes (e.g., insects and diseases); and (2) abiotic disturbance processes (e.g., fire and drought)</td>
</tr>
<tr>
<td>4. Conservation and maintenance of soil and water resources</td>
<td>Five indicators describing forest soils and water conditions along with efforts to conserve them</td>
</tr>
<tr>
<td>5. Maintenance of forest contribution to global carbon cycles</td>
<td>Three indicators describing (1) forest carbon pools; (2) carbon pools in long-lived forest products; and (3) avoided carbon emissions from using wood to produce energy</td>
</tr>
<tr>
<td>6. Maintenance and enhancement of long-term multiple socioeconomic benefits to meet the needs of societies</td>
<td>Twenty indicators describing (1) the production and consumption of forest products; (2) investments in the forest sector and related human capital; (3) forest employment and community conditions; (5) forest-based recreation and tourism activity; and (5) cultural and spiritual values associated with forests</td>
</tr>
<tr>
<td>7. Legal, institutional and economic framework for forest conservation and sustainable management</td>
<td>Ten indicators describing legal, economic, and other institutional arrangements for forest planning and management, public participation mechanisms, economic incentives and monitoring efforts</td>
</tr>
</tbody>
</table>

Source: [23,25].

2. Study Area

Nine tropical island jurisdictions having political associations with the U.S. federal government ranging from statehood (Hawaii) to the freely associated nations of Micronesia and Palau were included in this study (Table 2). These jurisdictions stretch across more than 16,000 km from the U.S. Virgin Islands, at the eastern most point, to the Republic of Palau, at the western most point (Figure 1). They span a considerable swath of longitude and latitude within the tropical belt and are subject to the many influences of island biogeography [26,27]. The group includes comparatively larger islands with mountain ranges exceeding 4000 m above sea level (masl) in the Pacific (i.e., Hawaii) and exceeding 1000 masl in the Caribbean (i.e., Puerto Rico) to relatively small, low lying, widely dispersed islands and atolls that do not exceed 10 masl (e.g., the Marshall Islands). Social-ecological characteristics and conditions vary across the islands, in relation to divergent geographies and histories of human settlement and use.

Table 2. Characteristics of the nine island jurisdictions in the study area (listed from east to west).

<table>
<thead>
<tr>
<th>Island Jurisdictions</th>
<th>Total Area (km²)</th>
<th>Political Status</th>
<th>Islands and Atolls</th>
<th>Population (2018)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caribbean</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U.S. Virgin Islands</td>
<td>346</td>
<td>Territory</td>
<td>4</td>
<td>106,977</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>8870</td>
<td>Commonwealth</td>
<td>3</td>
<td>3,195,153</td>
</tr>
<tr>
<td>Pacific</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hawaii</td>
<td>16,635</td>
<td>State</td>
<td>7</td>
<td>1,420,491</td>
</tr>
<tr>
<td>American Samoa</td>
<td>199</td>
<td>Territory</td>
<td>6</td>
<td>50,826</td>
</tr>
<tr>
<td>Guam</td>
<td>544</td>
<td>Territory</td>
<td>1</td>
<td>167,772</td>
</tr>
</tbody>
</table>
3. Methods

Criteria and indicator frameworks for resource measurement, monitoring, and reporting generally require or rely on established data sources and streams to populate indicators with information on conditions and trends. In our application of the MP C&I, first we identified available data sources for each criterion and its associated indicators at the jurisdiction level. We also identified related reporting activities from which we could draw relevant and related data. Some regularly collected data were available for a limited number of indicators, mostly related to biophysical elements and basic human demographics, but many of the indicators relied on one-time studies, proximal data, and/or anecdotal information.

Once available data streams and other relevant information were identified, we assembled and analyzed the data within and across criteria and island jurisdictions, combining indicators where data were limited or adjusting indicator focus to fit the island setting. We then analyzed the similarities and differences at different scales within the MP C&I framework and within and across the nine island jurisdictions. This analysis, however, did not include testing of all or specific indicators against sustainability thresholds—rather, we used the MP C&I to organize and present information on forests in a synthetic fashion.

Social-ecological heterogeneity across and within island jurisdictions is one of the study’s most salient aspects and presented considerable challenges for a comprehensive assessment of forest sustainability for the region as a whole. Nevertheless, assessing the islands side-by-side, regionally, and altogether permitted the identification of similarities and distinctions in terms of their ecological, economic, and social conditions and trends, as well as opportunities and red flags to be carefully considered when contemplating their sustainability and related policies and practices. (Detailed data collection and analysis methods at criterion level are described further in McGinley et al. [23]).

4. Results

In the sections that follow, we present key results by Montreal Process criterion at aggregate, regional, jurisdictional, and sub-jurisdictional levels, where available. We also discuss the availability and adequacy of data for reporting on forest sustainability at the criterion level.

4.1. Conservation of Biological Diversity: MP Criterion 1

Criterion 1 focuses on the biological diversity of forests at ecosystem, species, and genetic levels, as well as related forest conditions and conservation efforts. We identified fairly extensive and reliable data on forest cover and ecosystem diversity for all island jurisdictions, and more modest levels of data on forest ownership, protection, species and genetic diversity, and risk of extinction for most jurisdictions.

Forests cover 1.285 million hectares of the nine island jurisdictions (i.e., 45.4 percent of total area) and encompass more than 25 forested life zones [30–34]. (The Holdridge Life Zone system empirically

### Table 2. Cont.

<table>
<thead>
<tr>
<th>Island Jurisdictions</th>
<th>Total Area (km²)</th>
<th>Political Status</th>
<th>Islands and Atolls</th>
<th>Population (2018)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Permanently</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inhabited</td>
<td></td>
</tr>
<tr>
<td>Republic of the</td>
<td>181</td>
<td>Nation</td>
<td>24</td>
<td>75,684</td>
</tr>
<tr>
<td>Marshall Islands</td>
<td></td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Federated States of</td>
<td>702</td>
<td>Nation with four states</td>
<td>~77</td>
<td>103,643</td>
</tr>
<tr>
<td>Micronesia</td>
<td></td>
<td></td>
<td>542</td>
<td></td>
</tr>
<tr>
<td>Commonwealth of the</td>
<td>464</td>
<td>Commonwealth</td>
<td>3</td>
<td>51,994</td>
</tr>
<tr>
<td>Northern Marianas</td>
<td></td>
<td></td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Republic of Palau</td>
<td>459</td>
<td>Nation with 16 states</td>
<td>8</td>
<td>21,516</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>250</td>
<td></td>
</tr>
</tbody>
</table>

Source: Hawaii and Puerto Rico—[28]; all others—[29].
defines the conditions for vegetation growth based on bioclimatic information (e.g., biotemperature, precipitation, and evapotranspiration) [35]. Vegetative community classes have not been fully developed for all of the islands and those that do exist have not been standardized across the islands or similar life zones. Therefore, we examined the islands’ forests according to the Holdridge Life Zones system, which can be used as a proxy for ecosystem or community type. Most of these islands were nearly completely to entirely forested prior to human occupation and many underwent some or, in many cases, a significant degree of forest conversion to agricultural and grazing lands, or to grasslands and badlands [36,37]. These land use changes occurred during periods of initial settlement, colonization, agricultural expansion, and related population growth, primarily on relatively accessible islands and those with more gently sloped terrain (e.g., the larger islands of Hawaii and Puerto Rico) [36–41]. Far less deforestation or conversion to other land uses, if any, occurred on the most isolated islands (e.g., those of Palau) or on those with forests on steep, rugged terrain and in very wet climates (e.g., Tutuila in American Samoa, high islands in eastern Micronesia). Today, forest cover ranges from 36 percent in Hawaii to 89 percent in Palau and all island jurisdictions but Hawaii are more than 50 percent forested (Figure 2).

**Figure 2.** Forest cover in hectares and as a percentage of total land area for U.S. and U.S.-affiliated tropical islands (CNMI: Commonwealth of Northern Mariana Islands, RMI: Republic of Marshall Islands, FSM: Federated States of Micronesia) Source: [30].

Many of the historically deforested island jurisdictions in the Caribbean and Pacific regions have since recovered a significant portion of once cleared forest areas through regeneration, planting, or both, mostly on agricultural lands that were abandoned with changes in socioeconomic dynamics tied to industrialization, urbanization, globalization, and other processes [37,38]. Some forest recovery also has occurred as a result of environmental legislation and conservation efforts [39]. Presently, a large portion of the total forest area across the islands is classified in early to middle stages of succession, dominated by smaller to medium diameter trees (<28 cm diameter at breast height (dbh)), indicative of younger-aged forests but also specific forest types, for example those found in drier conditions (Figure 3). Forested area in three Pacific jurisdictions is dominated by trees >28 cm dbh) attributed in part to the presence of coconut trees in forest plantations and agroforests [42].
When considering forests that are officially protected or actively managed and where land use change is prohibited, Hawaii has the most protected or managed forest area at 43 percent [47]. American Samoa, Guam, and Palau have at least 20 percent of their forested land protected in these categories [48] and the remaining five jurisdictions between 10 and 20 percent [48–50]. Many of the islands also have other long established or more recently developed forms of forest protection through traditional practices, collaborative arrangements, and private measures, but these are not directly measured or tracked over time.
Owing in part to their relatively small land bases and isolation from continental land masses, the forests across these Caribbean and Pacific islands do not host the high levels of species richness found in mainland tropical areas, but they are relatively rich in plant and animal species on a per unit of area basis, particularly if compared to temperate systems. Hawaii has at least 10,843 documented terrestrial plant and animal species, Puerto Rico has 8980, and the U.S. Virgin Islands 2976 (includes terrestrial mammals, birds, freshwater fish, amphibians, reptiles, insects, and vascular plants) [51–59]. Puerto Rico demonstrates the highest species richness rate on a per unit area basis of the three, but caution is warranted in comparisons of species richness rates given variation in the level of documentation efforts per taxonomic group and island jurisdiction. Some scientists have described Hawaii’s tropical forests as a “low-diversity extreme” within the global range of tropical forest diversity, attributed in part to their relatively young geological age (i.e., <1 million years) and to their remoteness, which results in longer distances and shorter time frames for plant colonization and subsequent speciation in the Hawaiian islands than older islands (e.g., Puerto Rico) or continental counterparts (e.g., Costa Rica) [60,61].

Across all jurisdictions, forest biota is comprised of native and non-native species, some of which were introduced 1000 years ago and even earlier as food, timber, medicine, or ornamental resources, and many of which have become naturalized [62,63]. For example, fruit trees like mangoes (Mangifera indica) and coconuts (Cocos nucifera) are common among the trees inventoried by the FIA program in the Caribbean and Pacific [30]. Actually, species richness has increased across most if not all islands, due to species introductions and eventual naturalizations that far outnumber native species extinctions [64,65].

The islands also host high numbers and rates of range-restricted species (e.g., endemic species) compared to most mainland tropical areas, due in part to the islands’ relative isolation, climate, and heterogeneity of habitats [9,27]. Hawaii demonstrates the highest levels of documented endemism among the nine jurisdictions, with more than 99 percent of its native terrestrial insects, spiders and land snails, 90 percent of its plants, and more than 80 percent of its breeding birds classified as endemic [55,66]. Owing in part to their relative proximity to other islands in the Caribbean and to the American mainland, Puerto Rico and the U.S. Virgin Islands have comparatively lower rates of species endemism than Hawaii. For example, just eight percent of Puerto Rico’s plants and about 20 percent of its resident breeding birds are endemic, but endemism is high among its herpetofauna (amphibians and reptiles) at 91 percent [52,53,65,67].

Six hundred and forty two terrestrial plant and animal species native to the nine island jurisdictions studied have been identified as critically endangered (301), endangered (195), or vulnerable (146) to extinction by the International Union for the Conservation of Nature (IUCN) (The IUCN Red List (http://www.iucnredlist.org) is based on standard criteria with quantitative thresholds for population and range size, structure, and trends used to assign species to categories of extinction risk from ‘least concern’ to ‘critically endangered’, as well as ‘extinct in the wild’ and ‘extinct’). (Table 3). The U.S. Fish and Wildlife Service (FWS) also lists species at-risk of extinction under the provisions of the Endangered Species Act and identifies 473 plant and animal species as endangered or threatened with extinction in the U.S. Virgin Islands, Puerto Rico, Hawaii, American Samoa, Marshall Islands, and Guam (the FWS does not develop species listings for the freely associated states). (There is approximately 70 percent concurrence between the species listed by the IUCN and FWS for the six jurisdictions addressed by both institutions. The IUCN lists proportionately more animals (54 percent), whereas the FWS lists proportionately more plants (71 percent). Differences in the lists likely are due to differing approaches to and criteria for species listings). Both lists include a large number of endemic species, whose extirpation could result in the extinction of the global population and a permanent loss to species richness worldwide. On a per unit of area basis, the rates of endangerment across these islands are similar to other biodiversity hotspots but generally higher than those found in the mainland tropics and orders of magnitude higher than those encountered in the continental United
States [68–70]. A wide array of on- and off-site efforts to protect at-risk forest species and their diversity occur throughout the islands, including jurisdictional, federal, and civil society efforts to protect and recover species and their habitat.

Table 3. At-risk forest associated plant and animal species listed by the International Union for the Conservation of Nature (IUCN) and by the U.S. Fish and Wildlife Service (FWS) in tropical islands of and politically affiliated with the U.S. (listed east to west).

<table>
<thead>
<tr>
<th>IUCN</th>
<th>FWS</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Critically</td>
<td>Endangered</td>
<td>Vulnerable</td>
<td>Endangered</td>
<td>Threatened</td>
</tr>
<tr>
<td>US Virgin Islands</td>
<td>10</td>
<td>11</td>
<td>5</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>35</td>
<td>33</td>
<td>28</td>
<td>57</td>
<td>12</td>
</tr>
<tr>
<td>Hawaii</td>
<td>204</td>
<td>87</td>
<td>62</td>
<td>339</td>
<td>8</td>
</tr>
<tr>
<td>Am. Samoa</td>
<td>2</td>
<td>9</td>
<td>10</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>Marshalls (RMI)</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Micronesia (FSM)</td>
<td>6</td>
<td>12</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N. Marianas (CNMI)</td>
<td>9</td>
<td>11</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guam</td>
<td>8</td>
<td>13</td>
<td>9</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Palau</td>
<td>27</td>
<td>16</td>
<td>8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: [71,72]; see websites for detailed category definitions.

The IUCN lists approximately 120 known extinctions of documented terrestrial species associated with these nine island jurisdictions since circa 1500 AD, almost 90 percent of which originally were found in Hawaii. Nearly 10 percent of recorded Hawaiian plants are presumed to be extinct [52]. Additionally, sixteen named forest bird species have gone extinct from Hawaii in historical times and another nine forest bird species are presumed or likely extinct [52,56,73,74]. These avian extinctions are attributed to a complex array of factors, including historical hunting by native islanders and European colonizers, predation by non-native species, introduced diseases, and habitat loss and fragmentation, and exacerbated by limited genetic diversity and population size and range, and many of these factors persist as pressures today [74]. Other known extinctions in the Pacific include nine of Guam’s 11 documented ground-dwelling birds, whose extirpation is largely attributed to predation by the non-native brown tree snake (Boiga irregularis) [75].

Documented extinctions in the Caribbean are somewhat lower than those reported for Hawaii, despite clearance and conversion of at least 95 percent of native forest to other land uses by the 1940s [76,77]. Use of shade trees in the coffee region and the growth of secondary forest patches across the island meant that forest cover never really fell below 10 to 15 percent, which aided in the protection of native fauna and flora [76]. Brash [78] documented the extirpation of seven known native Puerto Rican bird species since human settlement (12 percent of originally documented bird fauna), including four endemic birds, but also documented the overall increase in breeding bird species on the island by the mid-1980s (97 species)—37 more than in pre-Colombian times.

4.2. Maintenance of the Productive Capacity of Forest Ecosystems: MP Criterion 2

Criterion 2 focuses on forest productivity and the sustainability of timber and non-timber forest product (NTFPs) removals. Given ongoing forest inventory activity conducted by the USDA Forest Service FIA program across all island jurisdictions, there were fairly extensive data on some aspects important for this criterion including forest stocking and planted forest area and composition. Data on wood and nonwood harvest levels were more limited, coming from single point-in-time studies or anecdotal evidence, and not directly comparable across jurisdictions.

Very little of the forested area in any jurisdiction is actively managed or harvested for timber or other wood products, with the exception of parts of Hawaii where there is a small, established, and active timber industry and a discernible area of forest plantations (about 28,500 ha; 4.7 percent of total forest area) [79]. Most of the forested land on these islands is dominated by small (<13 cm dbh)
and medium (<28 cm dbh) diameter trees (except the Marshall Islands where non-timber coconut trees account for higher average diameters) (Figure 3), indicative of younger aged stands in the process of recovery, but also reflecting typical structural characteristics associated with drier climatic conditions on some islands, as well as the effects of frequent storms and other nonhuman and human disturbance processes common throughout the islands [32–34,43–46,80–83]. Very limited amounts of wood found in these forests are suitable for solid wood products at present, but more may be so in the future depending on stocking, growth rates, and applied management practices.

Forest plantations cover a total of at least 32,000 ha in the U.S. Virgin Islands, Puerto Rico, Hawaii, Guam, and Palau, 86 percent of which are located in Hawaii (no data were available for the other jurisdictions). These plantations are primarily stocked with non-native timber species, including Eucalyptus spp., Swietenia spp., and Tectona spp.; some were planted for the primary purpose of timber production and others for watershed protection or restoration [79,84–87]. Hawaii is the only jurisdiction with any measurable, albeit limited, commercial timber extraction from planted and natural forests, and the only jurisdiction that actively manages planted forests for timber production. Nevertheless, inventory data from planted forests available for wood production in Hawaii indicate that the majority are over-mature or undermanaged, such that their overall productivity is diminished, at least from the perspective of maximizing timber production [88,89].

Forests are important sources of artisanal and craft wood products in all jurisdictions and are important sources of wood for building and canoe materials in the Pacific. Fuelwood is collected from forests throughout both regions and is particularly important in the Pacific islands. There is some indication that the harvest of a few specific nontimber forest resources in certain settings is approaching or exceeding available stocks, particularly in the case of Santalum spp. and Acacia koa in Hawaii [89] and fuelwood collected from mangrove forests in the Federated States of Micronesia [90]. Nevertheless, nontimber wood product harvests are not actively monitored in any jurisdiction. Island forests also are important sources of nonwood forest products, such as nutritional, artisanal, recreational, cultural, and spiritual resources, which are particularly important in the Pacific islands where forests frequently are relied upon for subsistence [5]. However, information on nonwood forest product growth and extraction is not systematically collected or analyzed in any jurisdiction.

4.3. Maintenance of Ecosystem Health and Vitality: MP Criterion 3

Criterion 3 focuses on forest areas affected by abiotic (e.g., land clearance, fire, storm, climate change) and biotic (e.g., insects, disease, non-native invasive species) factors beyond “reference conditions” (a term that remains open to interpretation). Some data on specific insects, disease, and other biotic factors that affect forests, as well as biotic factors, including storms and forest conversion to other land uses, were available across all jurisdictions to varying degrees. Yet, comparatively very little data were available on the area or percent of forest affected by any of these factors beyond the reference point of pre-settlement conditions.

Forest land clearance was a widespread and significant disturbance during colonization of many of the islands, as discussed above, and continues to occur, albeit on a greatly reduced scale, mostly for development [32–34,38,43–46]. Fire occurs naturally on islands with active volcanoes, but fire from lightning strikes is rare [91,92]. Apart from lava ignitions, most fire affecting the islands’ forests is anthropogenic and has increased since human settlement and subsequent population expansion, particularly in the western Pacific, where it occurs in non-native and novel grasslands and along forest edges, and in dry areas of Hawaii and of southern and western Puerto Rico [91,92]. Storms, including hurricanes (in the Caribbean) and typhoons (west of the international dateline) are a regular phenomenon in the tropics and range in their strength and frequency and in their effects on the islands’ forests from one point or period of time to another. Yet, as extreme weather events are predicted to occur more frequently and increase in intensity with the changing climate [2,3], the capacity of some forest species and ecosystems to recover from storms may be moderated by the effects from local land use histories and the influence from other disturbances (e.g., fire, non-native species introductions) [93].
In addition, although many of the effects of climate change may still be largely within the range of natural variation, increased flooding intensity and events and salt water intrusion associated in part with climate-induced sea-level rise already are in evidence in some jurisdictions, particularly in lower lying and atoll islands (Table 4) [94–96].

Table 4. Relative sea level trends and equivalent 100 year change reported by the U.S. National Oceanic and Atmospheric Administration based on monthly mean sea level data over the entirety of the available data range measured by tide gauges at long term monitoring sites in the Caribbean and Pacific (listed east to west) [97].

<table>
<thead>
<tr>
<th>Station Location</th>
<th>Data Range</th>
<th>Relative Sea Level Trend (mm)</th>
<th>95% Confidence Interval</th>
<th>Equivalent 100 Year Change (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lime Tree Bay, U.S. Virgin Islands</td>
<td>1977–2018</td>
<td>2.50</td>
<td>+/-0.71</td>
<td>0.250</td>
</tr>
<tr>
<td>Charlotte Amalie, U.S. Virgin Islands</td>
<td>1975–2018</td>
<td>2.06</td>
<td>+/-0.63</td>
<td>0.207</td>
</tr>
<tr>
<td>San Juan, Puerto Rico</td>
<td>1962–2018</td>
<td>2.04</td>
<td>+/-0.39</td>
<td>0.204</td>
</tr>
<tr>
<td>Magueyes Island, Puerto Rico</td>
<td>1955–2018</td>
<td>1.82</td>
<td>+/-0.31</td>
<td>0.183</td>
</tr>
<tr>
<td>Nawiliwili, Hawaii</td>
<td>1995–2018</td>
<td>1.67</td>
<td>+/-0.43</td>
<td>0.167</td>
</tr>
<tr>
<td>Honolulu, Hawaii</td>
<td>1905–2018</td>
<td>1.49</td>
<td>+/-0.21</td>
<td>0.149</td>
</tr>
<tr>
<td>Mokuoloe, Hawaii</td>
<td>1957–2018</td>
<td>1.45</td>
<td>+/-0.53</td>
<td>0.149</td>
</tr>
<tr>
<td>Kahului, Hawaii</td>
<td>1947–2018</td>
<td>2.18</td>
<td>+/-0.41</td>
<td>0.219</td>
</tr>
<tr>
<td>Hilo, Hawaii</td>
<td>1927–2018</td>
<td>3.08</td>
<td>+/-0.30</td>
<td>0.308</td>
</tr>
<tr>
<td>Pago Pago, American Samoa</td>
<td>1948–2009</td>
<td>2.11</td>
<td>+/-0.81</td>
<td>0.223</td>
</tr>
<tr>
<td>Kwajalein, Marshall Islands</td>
<td>1946–2018</td>
<td>1.88</td>
<td>+/-0.68</td>
<td>0.189</td>
</tr>
</tbody>
</table>

The islands also differ in the degree to which their native ecosystems have been affected by biotic agents and processes, such as insects, disease, and non-native species deemed invasive (i.e., found to be spreading, regarded as a threat to a native species or ecosystem, and/or causing negative socio-economic impacts). Data from the FIA on forest health do not indicate any widespread tree effects from insects or diseases on trees, with the exception of the Republic of the Marshall Islands, where 18.5 percent of trees were affected by insects, all by foliar injury to one tree species, *Scaevola taccada* [82]. Hawaii also may be an exception, with some evidence indicating that Koa wilt (*Fusarium oxysporum*, affecting *Acacia koa*) is present on all Hawaiian islands at elevations up to about 2100 m with high incidence and mortality rates found in Koa plantations below about 900 m in elevation [98,99].

Non-native plant and animal species have been introduced in large numbers to the islands, intentionally or unintentionally, by early island settlers to current residents and modern commercial activity. Of these introductions, some are valuable or harmless, some have become naturalized, and some have spread to the point of negatively affecting native species or ecosystems and/or having negative socioeconomic effects. The numbers of invasive terrestrial species listed in the Global Invasive Species Database (GISD) administered by the IUCN range from 48 in the U.S. Virgin Islands to 247 in Hawaii (Table 5).
Table 5. Number of documented invasive terrestrial species in the U.S. and U.S. affiliated tropical islands (listed east to west).

<table>
<thead>
<tr>
<th>Taxonomic Group</th>
<th>Number of Documented Invasive Species</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>USVI</td>
</tr>
<tr>
<td>Mammals</td>
<td>7</td>
</tr>
<tr>
<td>Birds</td>
<td>1</td>
</tr>
<tr>
<td>Amphibians</td>
<td>3</td>
</tr>
<tr>
<td>Reptiles</td>
<td>0</td>
</tr>
<tr>
<td>Insects</td>
<td>12</td>
</tr>
<tr>
<td>Snails</td>
<td>0</td>
</tr>
<tr>
<td>Plants</td>
<td>25</td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
</tr>
</tbody>
</table>


In the extreme case among the islands, Hawaii has seen some 10,000 plant species introductions since initial settlement [52], of these about 1150 grow naturally outside of cultivation, and 176 are listed as invasive in the GISD, by far the most listed for any jurisdiction. Hawaii also accounts for the highest number of invasive animals listed by the IUCN. Animals deemed invasive affecting island forests include feral and unmanaged ungulates (e.g., pigs, goats) that overbrowse or trample established and emerging forest vegetation, and non-native predators (e.g., snakes, rats, cats) that prey on native birds and other animals, including their eggs, which can cause attendant secondary effects on pollination and dispersal [101,102].

A key consideration for many of these islands centers on the effects of non-native species introductions on native biodiversity. For instance, do non-native species replace native species, leading to localized or permanent extirpation?; do they co-occur with native species without significant negative effects in native populations?; do they provide a favorable environment for native species regeneration? The answers to these questions are specific to particular species, locations, and points in time. In Puerto Rico, where forest recovery may be further advanced than most jurisdictions in the study, mono-specific stands of non-native plants that once dominated abandoned agricultural sites have since given way to novel forest communities comprised of new combinations of native and non-native species that function and provide multiple ecosystem services at levels similar to or higher than native forests [103,104]. For example, the introduced African tuliptree (*Spathodea campanulata*) currently accounts for the greatest number of trees and most live tree basal area of all tree species inventoried by the USDA Forest Service FIA program, yet the next three most important tree species are native to Puerto Rico, demonstrating the capacity of native species to regenerate and compete with non-native species and their ability to recolonize secondary forest associations in landscapes significantly altered by human activities [43]. Introduced plant species in Puerto Rico include 16 documented invasive tree species listed by the Global Invasive Species Database out of a total of 123 introduced tree species documented by Francis et al. [105]. Many of these non-native species have extended their range in the wild, yet none have been documented to permanently replace native tree species in Puerto Rico.

A quite different process has been documented in Hawaii, where some native forest species have not been as successful in competing with or fending off non-native species, attributed in part to their evolution across niches and in near isolation, such that fewer species are able to outcompete the broad range of growth strategies demonstrated by some non-native plant species or are not equipped with self-defense mechanisms to fend off predation or herbivory by some non-native animal species [106]. Documented shifts in Hawaii’s forest composition have resulted from the spread of non-native species that eventually dominate areas previously classified as native forest, including stands of native Ohia (*Metrosideros polymorpha*) that have become dominated by Albizia (*Falcatoria moluccana*), a non-native
4.4. Conservation and Maintenance of Soil and Water Resources: MP Criterion 4

Criterion 4 focuses on the status and conservation of forest soil and water resources, including the area and percent of forests designated specifically for soil and water protection. Qualitative data on forest conservation efforts were available for all jurisdictions, but quantitative, comparable data on forest water and soil conditions were quite limited.

Much of the islands’ secondary forest area occurs on compacted, eroded, or otherwise degraded soils and with diminished water resources owing to the land use histories that predate them. In some areas, the establishment and maturation of these secondary forests actually contributes to the recuperation, maintenance, or protection of soil and water resources (see for example [38]). On many of the inhabited islands and particularly notable in Hawaii and part of the Pacific are the effects of feral ungulate (e.g., pigs, goats) activity that results in uprooting of vegetation, exposure of soil and subsoil, and dispersal of non-native grasses and other plant species in forests from early to late successional stages [113,114]. Water withdrawals and diversions from forested areas also occur to varying degrees where available, but water extraction levels and the associated effects on forests have been little studied (for exceptions see [115,116]).

Forests across the islands are protected for a range of values, including the conservation of soil and water resources to varying degrees (see Section 4.1). Forests also have been (re)planted on most islands for the primary purpose of watershed restoration or protection. In the Caribbean, the protection of riparian zones is mandated by law but rarely monitored or enforced [117,118]. Additional measures have been taken to protect and conserve the soil and water resources in critical watersheds through active partnerships between government, civil society, and the private sector in a few jurisdictions, including efforts led by the Hawaii Watershed Protection Board and watershed protection efforts initiated through the Micronesia Challenge. Voluntary best management practices (BMPs) for forest use and conservation that include the protection of soil and water resources are available in Hawaii and Puerto Rico. Additionally, the USDA Forest Service Forest Stewardship Program, which is active in most jurisdictions, promotes long-term forest management that takes into account soil, water, wildlife, and other forest values through technical and financial assistance for forest planning and operations.

4.5. Maintenance of Forest Contribution to Global Carbon Cycles: MP Criterion 5

Criterion 5 focuses on carbon stocks and fluxes in forests. Forest carbon estimates for Puerto Rico and the U.S. Virgin Islands were available from the FIA and forthcoming for the other jurisdictions based on the most recent measurements but not available at the time of this study. Very little to no data on forest product carbon stocks and fluxes or avoided fossil fuel carbon emissions from the use of wood as energy were available for the islands.

Carbon stock estimates range widely across the islands owing to their size, and forest area, types, and conditions. For instance, aboveground carbon (C) stocks in live trees greater than 2.54 cm were estimated at 20.4 million metric tons and 41.47 metric tons/ha in Puerto Rico and 0.55 million metric tons and 30.3 metric tons/ha in the US Virgin Islands [33,34]. Carbon stocks in the islands’ forests generally fluctuate in response to storms, hurricanes or typhoons, and other disturbances that can lead to short term losses followed by increases as forests recover [119]. Furthermore, while total island forest carbon stocks generally are small compared to continental levels, some stocks such as those in forest wetland soils across the islands, including mangroves, are relatively large per unit of area [120].
In Hawaii, total carbon stored in terrestrial ecosystems across the main islands (i.e., Hawaii, Maui, Molokai, Lanai, Kahoolawe, Oahu, Kauai) was estimated at 258 million metric tons of carbon in 2014 and showed an average annual increase of 20.2 metric tons of carbon between 2003 and 2014 [121]. Puerto Rico also has been a carbon sink for decades with net positive fluxes as forests have recovered and expanded, but these fluxes have tapered off and may be approaching net zero change as forest expansion levels off [33,43]. In the U.S. Virgin Islands, net losses of forest carbon resulting from the loss of forested area were reported during 1994–2004, but these negative carbon fluxes largely have tapered off since as forest loss slowed and approached stability [34,44]. Data on carbon fluxes were not available for other jurisdictions.

4.6. Maintenance and Enhancement of Long-Term Socioeconomic Benefits: MP Criterion 6

Criterion 6 focuses on the socioeconomic dimensions of forest sustainability. Data focused on forest benefits, activities, and other forest-related socioeconomic dimensions for addressing this criterion were very limited and, when available, mostly disparate and difficult to compare across the islands. Well-defined forest economic sectors are generally associated with multiple statistical measures that can be used to examine this criterion, but such sectors are largely absent in the islands. Given these data limitations, we examined this criterion at the sub-criterion level (rather than examining the 20 associated indicators individually), considering (1) production, consumption, and trade in forest products; (2) investment in the forest sector; (3) forest employment and community needs; (4) recreation and tourism; and (5) cultural, social and spiritual aspects, though even at this more general level data restrictions applied.

Production of wood and nonwood products from forests occurs in all jurisdictions (e.g., lumber, craftwood products, musical instruments, fuel, fiber, fruits, game meat, medicinals, resins, oils, etc.), though the magnitude of these production activities is largely unspecified in the data [85,86,89,90,122–126]. Some of these products are sold in local or even export markets, albeit in very limited cases, some are bartered, and many are used for subsistence. Forest food production through gathering, hunting, and agroforestry is important for many island inhabitants and for local livelihoods and economies, and is reflected in part in the pervasiveness of fruit and other food trees throughout much of the islands’ forests. In the Republic of the Marshall Islands, studies have shown that copra production, handicrafts, and “subsistence” use of forests comprise 54 percent of overall household production [5,30,127,128]. Other studies have demonstrated the importance and economic value of forest products, including mangrove crabs, wild pig meat, and wood to subsistence economies in Micronesia (see for example [129,130]).

Forested areas across the islands also serve as sources of recreation, aesthetic beauty, spiritual sustenance, and often are tied to a profound sense of place for many island inhabitants, but these elements are difficult to quantify and have been little studied in the islands. Tourism, in particular, is an important sector in all jurisdictions and occurs at industrial scale in Hawaii, Guam, the Northern Marianas, Puerto Rico, and the Virgin Islands. Forests often are among the primary tourism attractions, but their contributions to the economic benefits associated with tourism are not clearly delineated or directly measured in any jurisdiction. Moreover, although forests are important to tourism and tourism may in turn contribute to a greater overall economic valuation of forests, the need to manage tourism activity associated with forests is broadly acknowledged, both from an ecological and social standpoint, particularly where recreation is unmanaged or exceeds a forest’s carrying capacity and where tourism development incurs forest land use change [85,86,89,90,122–126].


Criterion 7 focuses on the legal, institutional, and economic framework that governs and promotes forest sustainability, addressing topics ranging from forest policy and laws, to public participation in forest decisions and management, to research and monitoring activities. Due to limitations in data for the 10 MP indicators, we consolidated our reporting to focus on local government institutions,
including land tenure and property rights, academic institutions, civil society organizations, cooperative activities, and regional collaborations supporting forests. These elements directly and indirectly address the overall focus of the criterion and information on them was available to some degree across all jurisdictions.

The heterogeneity that characterizes the ecological and social conditions in the islands is equally evident in their institutional, legal, and economic arrangements, attributable in part to their geography and to the histories and traditions unique to each of the islands. The size and nature of local government organizations determine in large part their ability to actively engage in forest management activities and to avail themselves of the various federal and international programs available to support these efforts. Five of the nine island entities have government units explicitly focused on forestry (i.e., U.S. Virgin Islands Department of Agriculture, Forestry Division; Puerto Rico Department of Natural and Environmental Resources, Forest Service Bureau; Hawaii Dept. of lands and Natural Resources, Divisions of Forestry and Wildlife; Guam Dept. of Agriculture, Division of Forestry; Republic of Palau Ministry of Natural Resources, Bureau of Agriculture, Forestry Section). The absence of explicitly identified, locally funded forestry agencies in the other four jurisdictions mostly reflects limited resources associated with smaller populations and governments but masks any integration of tropical forestry with other land management policies and programs such as those focused on coastal management or agriculture, programs that are common across all jurisdictions.

Jurisdiction-level laws, policies, and other institutions also are influenced by the association each has with the United States government, ranging from statehood (Hawaii) to commonwealth or territorial status (Commonwealth of the Northern Mariana Islands, American Samoa, Guam, Puerto Rico, and the U.S. Virgin Islands) to independent countries in compacts of free association with the United States (Federated States of Micronesia, Republic of the Marshall Islands, and Republic of Palau) (Table 2). These different types of association each carry different rights, constraints, and institutional arrangements in regards to the U.S. Government in general and federal land management and environmental laws and agencies in particular. Applicable U.S. national laws and regulations protect public benefits arising from forests and prevent negative effects to natural resources such as wetlands, water and air quality, wildlife, and threatened and endangered species to varying degrees in all jurisdictions. For instance, the Endangered Species Act of 1973 (ESA; 7 U.S.C. § 136, 16 U.S.C. § 1531 et seq.) is applied in all the islands, including the freely associated states of Micronesia, Palau, and the Marshall Islands as a legacy of these islands’ status until 1986 as Trust Territories administered by the United States.

All jurisdictions have systems in place that identify property and outline the rights associated with that property and its transfer, including due process relative to the loss of property or property rights. Four Pacific jurisdictions forbid outright land ownership by individuals that are not native or of island descent (i.e., Federated States of Micronesia, Commonwealth of the Northern Mariana Islands, Republic of the Marshall Islands). In these islands, dual tenure systems are common, with lands governed by private or public property rights that also fall under communal property regimes or tenure arrangements, which may be governed by a chief or Matai. In the Caribbean and the state of Hawaii, cultural and historical traditions are recognized through historical preservation laws, but no property rights or land tenure privileges are accorded through traditional practices or to any one group to the exclusion of others.

Academic institutions on the islands range considerably in their size and the degrees they confer; all jurisdictions have degree programs in agriculture, most in natural resources or environmental sciences, but none with an undergraduate or graduate degree in forestry or forest resource management and conservation. All but Palau and the Republic of the Marshall Islands host land-grant universities or colleges and receive Hatch and Smith-Lever funding for agricultural research and extension, including forestry and agroforestry programs. Civil society organizations also play a prominent role in promoting resource conservation and local development needs throughout the islands. They facilitate community participation and often act as a link between local, national, and international
actors and their related resources. Additionally, regional collaboration provides an opportunity for islands to pool their resources, learn from each other, and leverage outside resources from academia, the federal government, or NGOs. The most significant development comes from the Pacific through the “Micronesia Challenge”, founded by the heads of state of the Republic of the Marshall Islands, Federated States of Micronesia, Commonwealth of Northern Mariana Islands, Guam, and Palau in 2006 to “effectively conserve” at least 20 percent of the terrestrial resources (land acreage) in each jurisdiction by 2020, with all well on their way to meeting this goal, including American Samoa, Guam, and Palau which already have met or surpassed it [48].

5. Discussion

5.1. Island Forest Conditions and Trends Important to Assessing Sustainability

When we considered available data on ecological, economic, and social forest conditions and trends across the nine island jurisdictions through the lens of the MP C&I framework, several trends stood out as having direct bearing on the overall question of forest sustainability. First, forest area across the islands has been relatively stable at regional and study-wide scales over the past decade or so (i.e., 2000s–2010s), with forest losses, attributed primarily to development pressures, largely being offset by forest gains mostly from ongoing forest recovery on abandoned agriculture and grazing lands [32–34,43–46]. This trend is a positive signal for sustainability, particularly when forest losses are prominent elsewhere throughout the tropics [1]. Still, net forest losses at jurisdictional and sub-jurisdictional levels do not meet this most basic element of sustainability, warranting further research and monitoring to understand the associated causes and drivers and inform sound practice and policy.

Second, some elements of the islands’ native biodiversity are threatened by multiple factors, including the loss of habitat and plant and animal species deemed invasive when they displace, disturb, prey on, or otherwise affect species to the point of population declines. These effects tend to be magnified where species endemism is high. Hawaii’s biota stands out amongst the islands, having been highly studied and having the highest numbers and rates of at-risk species across major taxonomic groups [52]. Many of these species are endemic and their extirpation or extinction would mean a decline in global biodiversity. Habitat loss and invasive species are the top two threats cited in the at-risk species listings across all jurisdictions and factor prominently in the designation of biodiversity hotspots that include both regions (i.e., Caribbean Hotspot, Polynesian-Micronesian Hotspots) [10–12,68].

Third, new or ‘novel’ assemblages of non-native and native plant species are maturing over large areas and portions of many of the islands, predominately on abandoned agricultural lands cleared of native forests long ago. These forests typically are dominated by non-native and by smaller- (<13 cm dbh) and medium-stemmed (13–28 cm dbh) trees, limiting commercial timber uses, for now at least, but contributing to the restoration and provision of ecosystem services at levels similar to or even higher than native forests [64,103,104,106]. The implications of this trend to sustainability depend greatly on the future trajectory of these novel ecosystems in the specific social-ecological settings in which they occur and how sustainability is defined and delineated in its component parts and processes. While we do not pretend nor attempt to solve here the ongoing debates associated with ‘native’ versus ‘novel’ (see for example [131–133]), we do contend that comprehensive assessments such as this, which provide socioeconomic as well as biophysical information, help us better understand the full dimensions of forest functionality, thus shedding light on this question, as well as more general questions about forest sustainability, desired future conditions, and appropriate management actions.

Other major findings include (1) the importance of island forests as sources of food, medicinal supplies, wood for crafts and construction, and other materials for cultural purposes and daily use. Although commercial timber production is limited to Hawaii, where it occurs only on a small scale, many islanders depend on forests for their livelihoods and subsistence, particularly in the Pacific, where
with the exception of Hawaii, per-capita incomes are less than half the U.S. average and subsistence activities are important supplements to other sources of nutrition, household income, health, and life quality. (2) The potential effects of climate change threaten entire islands and ecosystems, given their susceptibility to sea-level rise, storm activity, and other disturbances, especially inhabited atoll islands that do not rise more than 10 masl [2,3]. (3) Limited domestic resources and insufficient economies of scale make it difficult to address these and other forest management challenges locally, though many islands actively engage in regional collaboration and exchange (e.g., in higher education) and have instituted cross-boundary partnerships incorporating nongovernmental organizations, citizens groups, local and federal governments, and private sector representatives to overcome some of these challenges and associated limitations.

5.2. Data Availability and Adequacy Important to Assessing Sustainability

Data availability and adequacy for assessing forest sustainability is an important meta-question that should be addressed in any comprehensive study such as this. We found that data that are both consistent over time and comparable across island jurisdictions are relatively rare. The USDA Forest Service has periodically measured forests through the FIA program in Puerto Rico since the mid-1980s and in the U.S. Virgin Islands since the mid-1990s, moving to cyclical measurements in 2014. More recently, the FIA completed a second measurement of forests in the Pacific islands, allowing for comparable status and trend data on forest area, species composition, tree age, volume stocking levels, and a variety of other biophysical measures across all jurisdictions, except Hawaii, which had only been measured once at the time of this study, though a second complete round of measurements are scheduled for 2019–2021 [30]. The establishment of consistent biophysical inventory activities constitutes a major improvement in data provision for management and assessment in the islands. U.S. Census and related socioeconomic information also are available but limited in their relation to forests and not always directly comparable across different jurisdictions, especially for the freely associated states (Republic of the Marshall Islands, Federated States of Micronesia, and Republic of Palau).

Improvements in data availability notwithstanding, much of the information required for comprehensive forest sustainability reporting in the tropical islands considered here is hard to find, reconcile, and compile, or it is simply unavailable. The lack of complete data is further compounded by island geographies, where heterogeneity makes comparison difficult and isolation makes measurement expensive. Noted data gaps include basic forestry information such as the distribution of species and forest soil and water conditions. On the social front, much of our understanding of the relationships between people and forests in the islands is based on anecdotal information and some scattered one-off studies, where it exists at all. In terms of institutions, we have yet to devise adequate measures, much less populate them with relevant data, even though we know that institutions are crucial to securing sustainable forest management.

5.3. Utility of the MP C&I in Assessing Sustainability in Tropical Island Forests

In general, the MP C&I’s stated focus on temperate and boreal forests did not present problems when applied to the tropical island forests included in this study. The biophysical indicators are general enough to be equally applicable in tropical settings. However, aspects of the MP C&I that focus on timber production were largely irrelevant to these islands at this point in time, since the majority have minimal to nonexistent wood products production activity. Conversely, many of the forest outputs and activities valued by island residents are under-represented in the MP C&I, and this is especially true in the area of agroforestry, common throughout the islands, particularly in the South Pacific. The MP C&I does contain a limited number of indicators on non-wood forest products and subsistence, as well as on forest-based recreation and cultural and spiritual values that are comparatively more relevant to the forests of these regions today, but our reporting in these areas is further limited by a lack of available data.
6. Conclusions

Forests on U.S. and politically affiliated islands of the Caribbean and Pacific are rich and dynamic social-ecological systems that, while distinct, have key characteristics and trends in common permitting cross-island analyses that underscore the utility of sustainability assessments that go beyond single jurisdictional efforts. Such efforts require some level of comparable data and in the last decade there has been notable progress in the measurement and monitoring of key biophysical aspects of forests on these tropical islands, permitting advances in the assessment of forest sustainability in the face of various stressors. In other areas, including social and economic forest dimensions, data availability remains a major challenge.

Through the flexible application of the MP C&I, we developed a fairly comprehensive view of forest conditions and trends within and across the islands. What emerges is a set of discreet pictures describing island conditions where net loss of forests is the exception, but dynamic changes associated with human habitation, new species introductions, and impending changes in climate present considerable challenges where human linkages to forests and their outputs are extensive even while major wood products production activities are rare.

We refrain from drawing any definitive conclusion about the ‘sustainability’ of Caribbean and Pacific island forests, but through a comprehensive depiction of these forests as systems, we identify areas where more analysis and, ultimately, policy responses merit increased attention. In this application, “sustainability” in general and the MP C&I in particular serve as organizing principles for the presentation of information, information that ideally will inform discussions, decisions and actions to address the many challenges facing these unique social-ecological systems and sustain them into the future.


Funding: This research was funded by the USDA Forest Service.

Acknowledgments: We thank Constance Carpenter who was instrumental in initiating this project and convening the collaboration between the Caribbean and Pacific regions. We also thank Ariel E. Lugo and two anonymous reviewers whose insightful comments improved this manuscript, and Thomas J. Brandeis and Humfredo Marcano-Vega for useful input and discussions on the data. The research was done in cooperation with the University of Puerto Rico.

Conflicts of Interest: The authors declare no conflicts of interest.

References


64. Mascaro, J.; Hughes, R.F.; Schützer, S.A. Novel forests maintain ecosystem processes after the decline of native tree species. *Ecol. Monogr.* 2012, 82, 221–228. [CrossRef]


73. Walther, M. Extinct Birds of Hawaii; Mutual Publishing: Honolulu, HI, USA, 2016; 238p.


75. Fritts, T.H.; Rodda, G.H. The role of introduced species in the degradation of island ecosystems: A case history of Guam. Annu. Rev. Ecol. Syst. 1998, 29, 113–140. [CrossRef]


79. Matsuwaki, D.H. Plantation Acreage by Island and Land Ownership Type; Unpublished Report; Department of Lands and Natural Resources, Division of Forestry and Wildlife: Honolulu, HI, USA, 2015; p. 96813.


91. Schultz, C.J.; Nauslar, N.J.; Watcher, J.B.; Hain, C.R.; Bell, J.B. Spatial, temporal, and electrical characteristics of lightning in reported lightning-initiated wildfire events. *Fire 2019*, 2, 18. [CrossRef]


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