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Forests of Palau: a long-term perspective

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Abstract—The Republic of Palau is an archipelago of the Caroline Islands (latitudes 8˚12' to 2˚48' and longitudes 131˚07' to 134˚44') with over 802 native plants of which 18.7% are endemic. Forest vegetation growth ranged from 0.04% to 0.22% yr^{-1} in three decades. Forest patches in Babeldaob showed differential growth rates with an overall rate of expansion of 38 m^2 yr^{-1}. Nine patches expanded at an average rate of 608 m^2 yr^{-1}, three patches decreased at a rate of 1267 m^2 yr^{-1} and 34 patches showed no change. Uncommon endemic species occurred in stable, wet and inaccessible areas of Babeldaob including *Parkia parvifoliola* and *Terminalia crassipes*. Dominant trees include *Campnosperma brevipetiolata*, *Horsfieldia* spp., *Maranthes corymbosa* and *Alphitonia carolinensis*. One large limestone island had a higher percentage of endemic trees (16.4%) than ten smaller limestone islands (11%). Within the island cluster, the larger islands had more species (mean = 26.8) than the smaller islands (mean = 7.8). A 2001 survey of 90 homes indicated that *Areca catechu*, *Cocos nucifera* and *Mangifera indica* were the most common trees. Year round and synchronous spring and fall flowering and fruiting was observed for dominant tree species. Endemic trees tend to have smaller fruits. Broad reproductive periods, easily dispersed seeds, seeds with thick exocarps and dwarfism are adaptations that may help trees survive climate change and human disturbance on small islands. The invasive trees, *Falcataria moluccana* and *Adenanthera pavonina* are considered threats to native forests. National land use and forest policies are needed to ensure that Palau's forests remain intact into the next century.

Introduction

The Republic of Palau is the westernmost archipelago of the Caroline Islands in Micronesia with 586 islands covering a land area of 535 km^2 (Figure 1). The archipelago extends 700 km northeast to southwest from latitudes 80˚12' to 2˚48' and longitudes 131˚07' to 134˚44' lying 900 km north of Irian Jaya, West Papua and 870 km east of the Philippines. Palau has a diverse assemblage of over 1,389 plants of which 802 are native and 571 are introduced. At least 150 of the native plants are endemic including 60 trees, 23 shrubs, 30 orchids, 17 herbaceous plants, 12 ferns, 4 vines and 4 with unrecorded growth forms. Palau may have the largest tract of tropical lowland forest in the Pacific (D. Mueller-Dombois, pers. comm. 2007). In 1979, nearly 218 km^2 or 52% of Palau's land

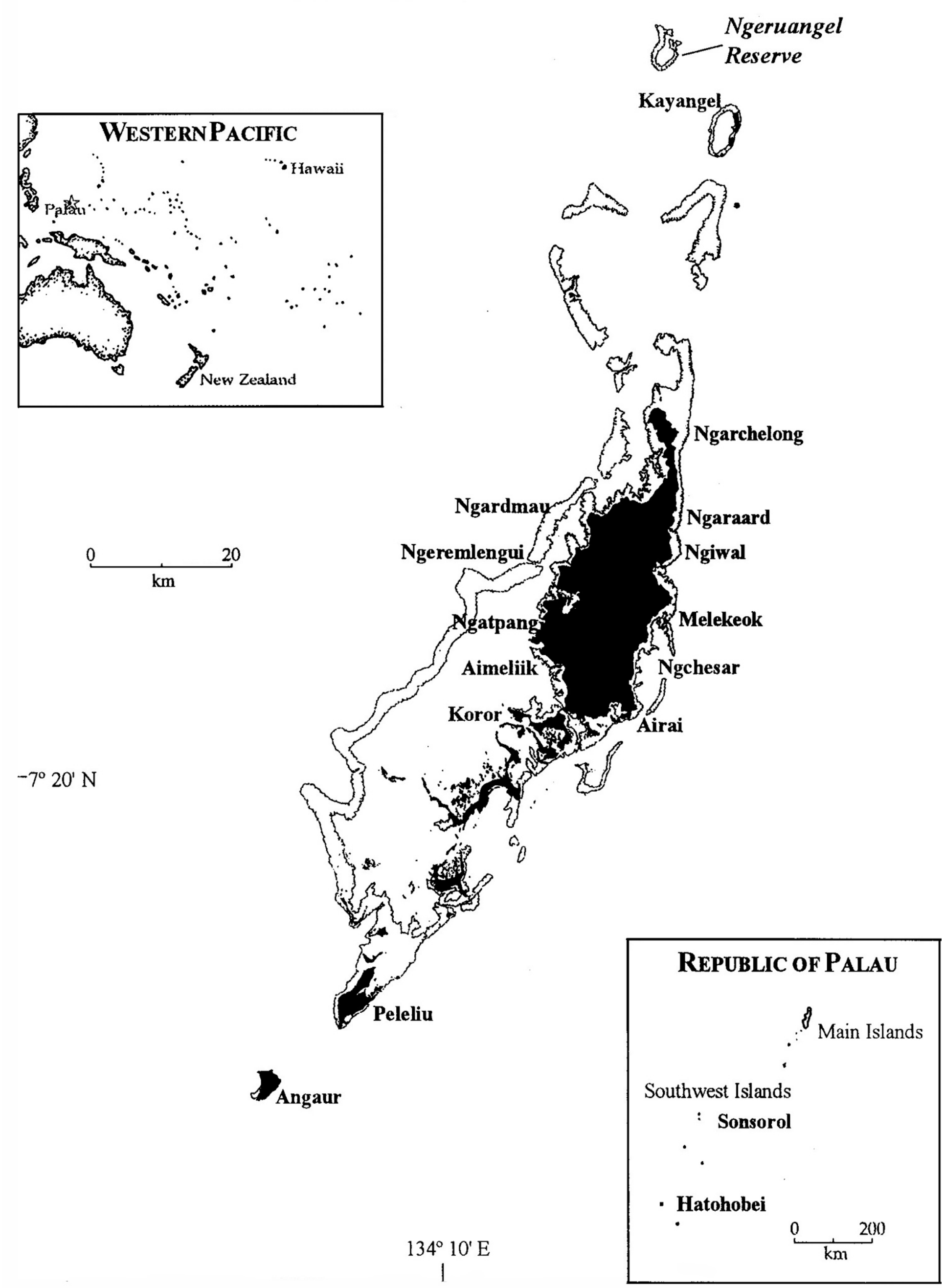

Figure 1. Map of Palau.

was covered with lowland forests. Yet, slowly forests are being cut for homesteads, development and roads. At least 2 km^2 or 1% of the lowland and swamp forests has been removed for development in the last few decades. Forest trees and plants are valued as sources of timber, food, medicine, as habitat for other species and for their cultural and aesthetic value. Palau's forests are important carbon sinks removing an estimated 98.57 Gg of CO_2 or 30% of Palau's total emissions (331.84 Gg) annually (OERC 2007). The objective of this paper is to present past and current information about the status of Palau's lowland forests, limestone forests, agroforest and, agricultural lands, urban forests, and mangroves. Forest cover, species composition, endemism, flowering and fruiting cycles, fruit morphology, invasive species and future research and recommendations are addressed in this paper.

GEOLOGY

The archipelago of Palau was formed during the Eocene epoch 40 million years ago by the subduction of the Pacific Plate beneath the Philippine Plate along the Kyoshu-Palau Ridge. Palau lies on the east edge of the Andesite Line, which divides the deeper basalts of the Central Pacific Basin from the partially submerged continental areas of andesites. Volcanism ceased 20 million years ago and was succeeded by submergence of islands and formation of the barrier reef began. During this same period of submergence, uplift occurred and the limestone islands and raised atolls of southern Palau were formed. The limestone formed beneath the sea and became exposed through uplift that occurred in the last 3-4 million years. Subaerial erosion formed the karst landforms seen today in the limestone islands (Kayanne 2007). Babeldaob, the largest volcanic island, covers an area of 365 km^2 (including 33 km^2 of mangroves) and extends 37 km in length and 6 to 13 km in width. The highest elevation for this old volcanic island is 213 m at Mt. Ngerchelchuus in central Babeldaob with the volcanic islands of Arkabesang, Malakal and Koror to the south.

CLIMATE

Palau has a tropical wet climate. On an average, the annual rainfall ranges from 3 to 4 m with a mean of 3.7 m per year. The dry period occurs from January to April and a wet period is from June to August. The humidity ranges typically between 75 to 85%. The mean air temperature is 27˚C and the maximum diurnal and seasonal variation is 5.5˚C. The large-scale near-surface water circulation is a westward-flowing North Equatorial to the North of Palau and an eastward-flowing Equatorial Countercurrent to the South of Palau. Palau is located in a recirculation zone. Palau has prevailing northeast trade winds from November to May and a southwest wind from June to October. The wind field around Palau varies with the topography of the land. Weak east trade winds prevail from December to April changing to southwest trade winds from May to October (Wolanski & Furukawa 2007).

PALEOENVIRONMENT

Paleoenvironmental studies using pollen grains of agricultural plants are reconstructing Palau's ancient past (Athens & Jerome 2004, Athens & Ward 2001, Liston 2005, Liston & Tuggle 2006, Masse et al. 2006). Palau is considered a "stepping" stone to the western Pacific. Human settlement dates back to 3000 calendar years before present (Liston 2005, Fitzpatrick 2002). Paleoenvironmental data and models for Austronesian ethno-linguistic expansion suggest that human settlement may have occurred by the mid fifth millennium (Athens & Ward, 2004). A series of complex terraces occur on Babeldaob that are hypothesized to have been used for intensive agriculture and defense. These terraces show evidence of erosion and abandonment as a consequence of intensive agricultural activities (Liston & Tuggle 1998, Masse et al. 2006). At least 50% of Palau may have been altered by past human activity (J. Liston, pers. comm. 2007). Intensive extraction of bauxite occurred in central Babeldaob and phosphate in the southern islands of Peleliu and Angaur and the Southwest Islands. Understanding the geological processes, climate and human activities is critical in order to understand the current patterns in plant biodiversity, distribution and abundance within Palau's forests.

Materials and Methods

The methodology used for this study included a literature review of existing work in Palau including vegetation surveys and taxonomic studies. Seed morphology and flowering and fruiting periods of selected species were based upon field observations made from 2003 to 2007 and information from herbarium voucher species at the Belau National Museum Herbarium, the New York Botanical Gardens, the University of Guam Herbarium and the Bishop Museum. Species status was based upon the literature review and ongoing work to update the Belau National Museum Herbarium database. In 2006, ERDAS IMAGINE software (Leica Geosystems, LLC) was used to rectify 1992 aerial imagery with 2005 Quickbird satellite imagery (DigitalGlobe Corp.) and conduct area analysis to determine forest change in southeastern Babeldaob.

Existing data from past surveys by Cole et al. (1987), MacLean et al. (1988), Kitalong & Holm (2004), Costion & Kitalong (2006), and Donnegan et al. (2007) was used to rank dominant species based upon either the proportion of the plots where the species occurred or the frequency of species were either measured or recorded at plots or stations. Data on tree frequency and diameters were derived from the 1988 Ngerukuid Preserve survey and raw data from the author from a terrestrial survey of Sngall Ridge. The data were used to compare species composition and relative abundance.

An urban forest survey was conducted at 90 homes in Koror and Airai (Kitalong 2001). Seventh and eighth grade students were trained to identify trees and measure their circumference (to the nearest centimeter) and estimate heights (to the nearest meter) within four 100 m^2 plots in the northeast, northwest, southeast and southwest directions of their homes. The students documented uses of each tree based upon interviews with their families.

Results

SYNOPSIS OF PAST FOREST RESEARCH

Palau's vegetation has been studied for many decades. Early work on Palau's flora described its *Campnosperma brevipetiolata* forests and plant associations (Hosokawa 1938, 1952, 1954). Flora systematics and plant communities of the forests and savannas have been researched by Fosberg for decades (Fosberg 1947, 1957, 1963, Fosberg and Sachet 1980). Wetland communities were surveyed and categorized by Stemmerman (1981). The cultural and economic aspects of taro cultivation were described by McCutcheon (1985). Cole et al. (1987) surveyed the vegetation of Palau. MacLean et al. (1988) surveyed the timber resources of Babeldaob. Birkeland & Manner (1989) surveyed and established baseline vegetation plots in the Ngerukuid Preserve. Canfield et al. (1992) conducted a rapid ecological study of the Ngeremeduu Bay Drainage Area. Raulerson et al. (1997) did a botanical reconnaissance for the proposed Compact Road in Babeldaob. Lorence & Flynn (2001) revised the checklist of plant species in Palau. Endress and Chinea (2001) studied landscape changes and addressed the importance of endemics in forest succession (Endress 2002) in the Ngeremeduu Bay Drainage Area. Kitalong & Holm (2004) did a preliminary assessment of Palau's forests. Costion & Kitalong (2006) surveyed important forest areas of Babeldaob. Donnegan et al. (2007) conducted a systematic inventory of the forests. Kitalong et al. (2007) are currently working on a provisional checklist of vascular plants of Palau. Lorence & Flynn (2007) are working on final revisions of a checklist of vascular plants for Pohnpei with much overlap with Palau's species. Each of these studies has contributed to our understanding of Palau's forests.

LOWLAND FOREST

Cole et al. (1987) estimated a forest cover of 80% including agroforest and secondary forest vegetation and 20% non-forest vegetation. Donnegan et al. (2007) estimated a forest cover of 82% including agroforest and secondary forest vegetation and 18% non-forest. Cole et al. (1987) covered 412 km^2 with a canopy threshold equal to or greater than 30% using 1976 aerial photography. Donnegan et al. (2007) covered 445 km^2 with a canopy threshold of equal to or greater than 10% using 2003 IKONOS (GeoEye Corp.) and 2005 QuickBird satellite imagery. Given the difference in canopy cover thresholds between 1987 and 2007 surveys, there was a 2% increase in forest vegetation in thirty years or a 0.07% yr^{-1}. Trends indicate that there may be some areas in Babeldaob where non-forest vegetation reverted to forest. Comparisons of the 1987 and 2007 surveys indicate that forested land in Babeldaob was maturing and may be encroaching slightly on non-forest vegetation. In contrast, Peleliu, Koror and Angaur were losing forest land to urban and non-forest vegetation land uses. Donnegan et al. (2007) estimated that 16% of the forest was limestone and 66% was volcanic.

MacLean et al. (1988) conducted a timber inventory using forty nine plots of which three plots were in swamp forest, five plots were in mangrove forest and 41 plots were in either limestone or volcanic forests of Babeldaob. Donnegan et al. (2007) delineated land cover using 54 permanent plots of which 11 plots were in limestone forest and 43 plots were in volcanic forest in Babeldaob and Koror. Donnegan et al. (2007) estimated 2,115 trees ha^{-1} (SE=68) compared to 3,168 trees ha^{-1} (SE=102) in 1988. The estimated basal area was 33.5 m^2 ha^{-1} in 2007 survey compared to 31.2 m^2 ha^{-1} in the 1988. The estimated tree volume per hectare was 192 m^3 (SE=296) in the 2007 survey compared to 122 m^3 (SE=188) in the 1988 survey. Donnegan et al. (2007) suggested that some trees were increasing in size while others died during a thinning phase. The 2007 inventory data further suggested there was a higher net wood volume in limestone than volcanic forests with less species per plot in limestone (10 species) compared to volcanic forests (12 species).

Endress & Chinea (2001) studied landscape change in the Ngeremeduu Bay Drainage Area, an 84 km^2 area located along the west central coast of Babeldaob. Their results showed that the forest increased by 10.9% and the grasslands decreased by 11.2% between 1947 and 1992. Therefore, the rate of forest growth over this 45 year period was 0.22% yr^{-1} or 3 times greater than the rate of growth estimated throughout Palau derived from the Donnegan et al. (2007) study. The majority of this transition occurred between 1947 and 1976 when 41.6% of the grassland cover was converted to forest. This conversion slowed substantially after 1976 as only 3.6% of the grassland areas were further converted to forest by 1992. Forests expansion was significantly associated with the location of abandoned agricultural communities. Over 92% of the forests expansion occurred within 100 m of established forests suggesting that nearby forests facilitate recovery following human disturbance. This may also suggest that agricultural lands originally within forested areas became reforested after abandonment because the soils were less degraded than open savanna areas.

Over a 13 year period (1992-2005), analysis of aerial images indicated that there was differential forest growth for 46 forest patches within a watershed area in Airai, southeastern Babeldaob, with an overall increase in forest size of 2.28 hectares or 0.5% (462.26 ha in 1992 to 464.54 ha in 2005) or a rate of 0.04 yr^{-1} which is slightly lower but within a similar range as the rate derived by Donnegan et al. (2007). Further analysis showed that the mean rate of expansion (±1 SD) was 38 ± 525 m^2 yr^{-1}. Nine of the forest patches increased in size at a rate of 608 ± 461 m^2 yr^{-1} with a maximum expansion of 1725 m^2 yr^{-1}. Three forest patches decreased in size at a rate of 1,267 ± 1,150 m^2 yr^{-1} with a maximum rate of loss of 2,594 m^2 yr^{-1}. A total of 35 forest patches remained unchanged. This preliminary study showed relatively slow forest growth in recent years in southeastern Babeldaob. More field investigations are needed to determine the composition of these forest patches and possible causes for these differential growth rates. Tree species commonly found along forest edges include the endemic *Trichospermum ledermannii*, *Macaranga carolinensis*, *Cerbera manghas*, *Rhus taitensis*, and *Maranthes corymbosa*; they have been observed to gradually expand into grasslands. These species are typically more stunted in growth in open edge areas than in the interior of the forest.

Given the different methodologies, forest vegetation cover is relatively constant over time. Forest coverage showed a 2% increase over a 30 year period from 1976 (80%) to 2005 (82%) or a rate of 0. 0.06% yr^{-1}. In western Babeldaob, forests expanded by 3.6% between 1976 and 1992. In southeastern Babeldaob, forest cover increased in size by 0.5% between 1992 and 2006. The vegetation landscape showed little change. More research at finer spatial and temporal scales would provide a better understanding of changes in vegetation landscape of Palau.

During 2004 and 2005, a semi-quantitative survey of Babeldaob was conducted to determine important forest areas of Babeldaob (Costion & Kitalong 2006). A total of 51 transects and 398 stations were covered in this study. At each station an area within a 20 m radius was assessed covering 1256 m^2 per station and a total area of 50 ha. An average of 5 transects and 40 stations were visited at each state. The stations were mainly in lowland forest (60%), followed by savanna (15%), riparian forests (11%), swamp forests (11%), limestone forests (4%), marshes (4%), mangroves (4%) and coastal forests (3%). The southern state of Airai has the only limestone forests in Babeldaob. Coastal forests were found along the northeastern coast of Babeldaob. During this survey over 342 plant species were recorded including 249 native plants, 31 introduced species; 47 species determined to genus and 21 undetermined plant species.

The most frequently encountered tree species found in the 1988, 2003 and 2005 surveys were ranked according to relative abundance (Table 1). The most common species were *Pinanga insignis*, *Maranthes corymbosa*, *Alphitonia carolinensis*, *Semecarpus venenosa*, *Campnosperma brevipetiolata*, *Horsfieldia palauensis*, *Horsfieldia irya*, *Gmelina palawensis*, *Rhus taitensis* and *Pouteria obovata*. The largest trees by volume were *Campnosperma brevipetiolata*, *Maranthes corymbosa*, *Horsfieldia irya*, *Pinanga insignis*, *Sonneratia alba*, *Rhizophora apiculata* and *Intsia bijuga* (Table 2). The dominant Families included Anacardiaceae, Clusiaceae, Fabaceae, Myristicaceae, Myrtaceae, Sapotaceae and Tiliaceae. Relative rankings differed between surveys as each survey was conducted in different habitats and locations in Palau. These findings corroborate with an earlier botanical reconnaissance study (Raulerson et al. 1997) and an earlier forest habitat study (Kitalong & Holm 2004).

Babeldaob has a rich assemblage of species within its secondary and primary forests. A large percentage of Palau has not been qualitatively or quantitatively surveyed, especially the less accessible forests along the central ridge and upper watersheds of Babeldaob and the many limestone islands. Remnants of primary forests are found along upper watersheds along this central ridge and steeply sloped and less accessible areas of the lower part of Babeldaob.

Table 1. Top tree species ranked according to surveys by MacLean et al. (1988), Donnegan et al. (2003) and Costion and Kitalong (2006), as well as months or year-round occurrence of observed or recorded flowering and fruiting.

Species	1988 Rank[1]	2003 Rank[2]	2005 Rank[3]	Flowers observed	Fruits observed
Pinanga insignis Becc.	1	1(240)	3 (272)	Year round	Year round
Maranthes corymbosa Blume	2	6 (63)	9 (224)	April to May	June to August
Alphitonia carolinensis Hosok.	3	9 (50)	14 (160)	March to June	May to July
Semecarpus venenosa Volk.	4.5	7 (58)	5.5 (262)	March, May to June, August to October	May to August, October, December
Campnosperma brevipetiolata Volk.	4.5	4 (72)	2 (298)	February to April, June, December	January to March, May to July
Eugenia reinwardtiana (Blume) DC.		5 (65)	16 (122)	July December	April, July to August
Eugenia spp.	6	2 (108)	1 (305)		
Gmelina palawensis H. J. Lam.	7	11.5 (49)	11 (194)	May to August, December	May to August, October, December
Rhus taitensis Guill.	8.5	14.5 (40)	5.5 (262)	June to August, December	July to October
Horsfieldia palauensis Kaneh.	10.5	3 (101)	4 (271)	Year round	Year round
Horsfieldia irya Warb.	8.5	22.5 (25)	23 (48)	April, June to August	June to July
Pandanus aimiriikensis Martelli	-	22.5 (25)	7 (257)	July November	June to July November
Garcinia matsudai Kaneh.	8	14.5 (40)	12 (191)	July	July to August
Pouteria obovata (R.Br.) Baehni	7	16 (37)	8 (227)	October, November	June to September, December
Elaeocarpus joga Merr.	10.5	11.5 (49)	18 (102)	May, October to November	March June to July November to December
Calophyllum inophyllum L.	10.5	17(34)	25 (17)	February to May, September to November	February to May, September to November
Atuna racemosa Rafin. ssp. *racemosa*		8 (56)	19 (88)	December	July to October, December
Macaranga carolinensis Volk.	12.5	11.5 (49)	10 (196)	Year round	Year round
Cyathea spp.		13 (46)	13 (180)		
Manilkara udoido Kaneh.	12.5	19 (29)	20 (44)	May, July, September to October, December	May, July, August, October

Table 1, cont'd.

Species	1988 Rank[1]	2003 Rank[2]	2005 Rank[3]	Flowers observed	Fruits observed
Astronidium palauense (Kanchira) Markgr.	16.5	18 (32)	15 (128)	February, October, December	October, December
Cerbera manghas L. or *Cerbera floribunda* K. Schumann	16.5	24 (21)	21.5 (73)	Year round	Year round
Fagraea ksid Gilg & Benedict	16.5	25 (19)	21.5 (73)	Year round	Year round
Glochidion spp.		20 (26)	24 (38)		
Symplocos racemosa var. *palauensis* (Koidz.) Noot.	16.5	25 (19)	17 (116)	February to April	May to August

Table 2. Tree species ranked by volume for the top 20 trees in the MacLean et al. (1988) and Donnegan et al. (2007) surveys.

Species	1988 Rank	2003 Rank
Campnosperma brevipetiolata Volk.	1	1
Maranthes corymbosa Blume	2	2
Horsfieldia irya Warb.	3	15
Pinanga insignis Becc.	4	7
Alphitonia carolinensis Hosok.	5	20
Gmelina palawensis H. J. Lam.	6	16
Calophyllum inophyllum L.	7	13
Rhus taitensis Guill.	8	14
Horsfieldia tuberculata (K.Schum.) Warb. var. *tuberculata*	9	5
Fagraea ksid Gilg & Benedict	10	
Pterocarpus indicus Willdenow	11	
Manilkara udoido Kaneh.	12	
Symplocos racemosa var. *palauensis* (Koidz.) Noot.	13	
Semecarpus venenosa Volk.	14	8
Cocos nucifera L.	15	6
Horsfieldia palauensis Kaneh.	16	3
Colona scabra (Sm.)Burret	17.5	
Elaeocarpus joga Merr.	17.5	9
Kopsia flavida Blume	19	
Cerbera manghas L. or *Cerbera floribunda* K. Schumann	20	
Sonneratia alba Sm.		4
Rhizophora apiculata Blume		5

Table 2, cont'd.

Species	1988 Rank	2003 Rank
Intsia bijuga Kuntze		6
Eugenia reinwardtiana (Blume) DC.		10
Atuna racemosa Rafin. ssp. *racemosa*		11
Bruguiera gymnorrhiza (L.) Lamk.		12
Vitex cofassus Reinw. ex Blume		16
Artocarpus mariannensis Trécul		18
Gmelina elliptica J.E. Sm.		19

Less common plant species observed in Babeldaob included the orchid, *Agrostophyllum palawense*, the herbaceous plant, *Hedyotis cornifolia*, the small tree, *Badusa palauensis*, and the larger tree, *Buchanania palawensis* that were found in Ngardmau. *Gynchthodes verticillat*a and *Melicope trichantha* were found in Aimeliik. *Medinilla blumeana* was found in Ngchesar and Ngardmau. The fern, *Adiantum palaoenses* was recorded in Ngchesar. *Premna pubescens* was found in Ngaremlengui and Ngardmau. In addition there were associations of endemics that were common in most States including the orchid, *Malaxis setipes*, the climbing Pandanus, *Freycinetia villalobosii*, and the smaller plants *Piper hosokawae*, *Hedyotis tomentosa* and *Phyllanthus palauensis*. Common large trees included *Calophyllum inophyllum* L. var. *wakamatsui*, *Horsfieldia palauensis*, *Calophyllum pelewense*, *Garcinia matsudai*, *Drypetes nitida*, *Casearia hirtella*, *Fagraea ksid*, *Symplocos racemosa* var. *palauensis*, and *Trichospermum ledermannii*. Common understory trees were *Pandanus aimiriikensis*, *Osmoxylon oliveri* and *Astronidium palauense*.

LIMESTONE ISLANDS

A comparison was made between a cluster of 10 rock islands in the Ngerukuid Preserve of the southern lagoon (7˚10' 36.53, 134˚15' 59) and Sngall Ridge, a part of a larger limestone island (7˚21' 06, 134˚29' 57) 32 km northeast of the Preserve (Table 3). *Eugenia reinwardtiana* was the most common tree species (24% or 140 of 580 trees measured) in the southern Ngerukuid Preserve followed by *Rinorea bengalensis* (13%), *Intsia bijuga* (8%), *Pleomele multiflora* (6%) and *Hydriastele palauensis* (5%). *Eugenia reinwardtiana* was the most common species in the northeastern limestone island of Sngall Ridge (22% or 337 of 1564 trees measured) followed by *Cleistanthus carolinianus* (7%), *Hydriastele palauensis* (5.4%), *Intsia bijuga* (5%) and *Pouteria obovata* (4.5%). At the Ngerukuid Preserve, three dominate endemic species represented 11% of all trees measured: these included *Hydriastele palauensis* (5%), *Sterculia palauensis* (3%), and *Timonius subauritus* (3%). At the northern Sngall Ridge, three dominate endemics represented 16.4% of all trees measured. These were

Cleistanthus carolinianus (7%), *Hydriastele palauensis* (5.4%) and *Horsfieldia palauensis* (4%). The trees *Cleistanthus carolinianus*, *Gmelina palawensis* and *Syzygium cumini* were not recorded in the Ngerukuid Preserve, but were found on Sngall Ridge. *Sygyzium cumini*, a known weedy and invasive tree in other parts of the Pacific, was common on Sngall Ridge. Further analysis of the data from the Ngerukuid Island Wildlife Preserve showed that the largest island (31 ha) had more plant species (n = 50) than the smallest island (0.04 ha) with 6 species. Within the island cluster, the five largest islands (mean ± 1SD = 9.9 ± 12.1 ha) were compared with the five smallest islands (0.31 ± 0.23 ha). The larger islands averaged more species (mean ± 1SD = 26 ± 15) than the five smaller islands (7.8 ± 2). The larger islands had a greater tree volume (mean ± 1SD = 135 ± 128) than the smaller islands (13 ± 5). More research is required to determine the distribution and abundance patterns and required habitat size for flora found on different sized islands along different latitudinal and longitudinal gradients.

AGROFORESTRY AND AGRICULTURE

Traditional agroforestry has been ongoing for centuries in Palau. Taro or *Colocasia esculenta* is intensely cultivated in swamps with multi-layered deposits of organic fertilizer using mainly banana leaves. Laborious land preparation of mud and canals with gates is required to regulate soil moisture. Yields can be up to 2.2 kg m^{-2}. Less intensive taro gardens do not require mud preparation. Dry land gardens are on lateritic soils with shallow, humus-rich topsoil. The taro swamp is surrounded by trees used for food, medicine and fertilizer and sometimes nearby homes, or it is found on clan lands at more distant locations. Traditionally, women cultivated taro with assistance from men for clearing large trees. Taro is an important customary food for Palauans for funerals, first birth ceremonies, marriage, and celebrations upon receiving a traditional title. Twenty years ago, McCutchen (1985) observed a trend towards more substitution of imported starches, reclamation of taro patches for homes and less community participation in traditional agroforestry. In recent decades, male laborers from the Philippines and Bangladesh are being used by women to work in their gardens as they pursue professional careers. This trend is ongoing as more and more customary celebrations substitute taro with rice.

Palau has been administered by foreign administrations that introduced dozens of plants to Palau for timber, food and medicine. Plantations of coconut trees, pineapple and cocoa occurred throughout Babeldaob. Mayo (1954) surveyed the Japanese Agricultural Station in Koror and commercial planting sites and relocated and recorded over 88 species of trees and plants of the originally recorded 157 planted. During 1922, the South Seas Industrial Experiment Station began the introduction and propagation of economic and subsistence plants. Pineapple production peaked in Ngaremlengui during 1939 when 473 hectares were cultivated by 468 Japanese families. The second most important crop was cassava (*Manihot esculenta*). In 1938, 113 tons of cassava was produced on 8 hectares of land. In 1936, cacao production began on 500 hectares of leased land in Ibobang, Ngatpang that resulted in a decade of profit. The shade tree, *Falcataria moluccana* was planted with cacao and Mayo reported that it was doing well in 1954. *Adenanthera pavonina* was planted in 1924. Several of the dominant trees planted during this time period included *Calophyllum inophyllum*, *Cananga odorata*, *Casuarina equisetifolia*, *Ceiba pentandra*, *Cocos nucifera*, *Coffea arabica*, *Diospyros blancoi*, *Ficus elastica*, *Garcinia mangostana*, *Hibiscus tiliaceus*, *Intsia bijuga*, *Mangifera indica*, *Metroxylon sagu*, *Pterocarpus indicus*, *Swietenia macrophylla*, and *Terminalia catappa*. *Swientenia macrophylla* grew well during this time period and became the preferred tree for reforestation in 1954 and is still planted today. Cole et al. (1987) identified two separate vegetation types as *Casuarina* Forest and Coconut Plantation. These earlier efforts of reforestation are still evident in the forest and urban landscapes today. Anthropogenic practices create habitat mosaics through moderate and repeated disturbance that can increase biodiversity at species, habitat and landscape levels (Smith & Wishnie 2000).

URBAN FOREST

During a 2001 survey of 90 homes in Koror and Airai State, a total of 859 trees representing 64 species and 37 families were identified and measured (Kitalong, 2001). A total tree volume of 596 m^3 was calculated or 0.016 m^3 m^{-2}. Eight plants represented 74% of the total volume: *Mangifera indica* (76 trees, 30% of total volume), *Areca catechu* (222 trees, 10%), *Cocos nucifera* (100 trees, 10%), *Terminalia catappa* (24 trees, 15%), *Swietenia marcophylla* (9 trees, 3%), *Spondias pinnata* (27 trees, 2%), *Plumeria obtusa* (22 trees, 2%), and *Artocarpus altilis* (11 trees, 2%). Other important trees and shrubs were *Musa* spp., *Persea americana*, *Syzygium aqueum* and *Nephelium lappaceum*. Less common trees included *Carica papaya*, *Citrus* spp., *Psidium guajava*, *Annona muricata*, *Premna serratifolia*, *Averrhoa carambola*, *Muntingia calabura* and *Bambusa vulgaris*. Decorative bushes and plants included *Gardenia jasminoides*, *Hibiscus rosa-sinensis* and *Cordyline fruticosa*. Large trees included *Serianthes kanehirae* Fosb. var. *kanehirae*, *Falcataria moluccana*, *Cananga odorata*, *Samanea* sp. and *Campnosperma brevipetiolata*. *Rhizophora mucronata* and *Calophyllum inophyllum* were found near homes adjacent to the mangroves and coasts. The students listed a total of 26 uses for 56 plant species. The most frequently cited uses were food, shade and decoration. Plants were used for lumber, medicine, drink, firewood, housing, chewing, furniture, flower leis, spice for soups and food, spears, animal food, holding the soil, wrapping materials for "bilum," making brooms, filling for pillows, clothing, slingshots, shelter, benches, income, glue and basket weaving. The coconut tree was listed with the most uses.

In 2007, an ethnobotanical study was initiated at the Belau National Museum Herbarium in partnership with the New York Botanical Gardens. Over 200 species have been collected to date and the uses documented and incorporated onto permanent labels for each voucher specimen. The names of each person who provided information about the uses of a plant are written on each label to ensure that the source of information is properly documented for years to come.

MANGROVES

Mangroves are the second largest forest type in Palau covering 48 km^2 or 11% of all vegetation. There are 29 species of mangrove-associated plants that are adapted to soft muddy substrate, oxygen poor soils and saltwater with modified roots, leaves, flowers and fruits. Dominant species include *Rhizophora mucronata*, *Rhizophora apiculata*, *Sonneratia alba* and *Bruguiera gymnorrhiza*. Certain species such as the mangrove holly, *Acanthus ebracteatus* and the mangrove tree, *Avicennia alba* had more restricted distributions based upon the limited surveys in this habitat. An estimated 1.43 km^2 of forests, 0.28 km^2 of wetlands and 0.6 km^2 of mangroves were reclaimed to build this national highway (TEI 2003). Using 2005 Quickbird imagery, an estimated 0.4 km^2 of mangroves has been lost in Palau for landfills, development and aquaculture. The National Highway completed in 2007 reclaimed an estimated 1.3 km^2 of mangrove forest. Thus, an estimated 1.7 km^2 of mangroves has been lost over the past 40 years at an estimated rate of 0.04 $km^2 yr^{-1}$.

Maragos et al. (1994) estimated mangrove cover at 45 km^2 compared to the current estimate of 48 km^2 or an increase of 3 km^2 in 15 years (0.2 km^2 yr^{-1}). A comparison of aerial photographs between 1968 and 2005 show that mangroves forests within Airai Bay nearly doubled in size (from 4.2 to 7.9 km^2) in a 37 year period at a rate of 0.1 km^2 yr^{-1}. These rough estimates indicate that the rate of increase in mangrove forests is 2.5 to 5 times greater than the rate of loss.

Airai Bay has become a mud bank and is silting at a rate of 150 tons $km^{-2}yr^{-1}$ (Golbuu et al. 2003). If siltation continues at its current rate it is estimated that the bay will be above sea level in 15 years (Victor 2007). This increase has been attributed to natural and accelerated growth due to increased sedimentation into the bay. Increasing populations, unplanned development and more frequent and intense rainfall result in accelerated rates of sedimentation which provides additional substrate for mangrove propagules to grow.

Accelerated sedimentation from soil erosion and mangrove expansion may not be a new phenomenon. This process may have been initiated thousands of years ago when the first immense terrace systems were created (Masse et al. 2006). Sediment cores with pollen grain analysis of agricultural and native plants would enable scientists to reconstruct more accurate time lines and to better determine relationships between human activities, sedimentation and forest dynamics for a given location over a longer time frame.

Stunted mangrove trees of *Sonneratia alba*, *Rhizophora mucronata*, *Bruguiera gymnorrhiza*, *Scyphiphora hydrophyllacea* and *Ceriops tagal* grow on marginal elevated areas such as raised man-made berms composed of coral fill from abandoned dredge sites. Inner zones of mangroves along southeastern Babeldaob have extensive stands of *Rhizophora apiculata* with stunted growth compared to larger forms of the same species along the seaward edge and adjacent to *R. mucronata*. Dwarfism may enable specific mangrove species to grow and reproduce in elevated, less optimum conditions and enable them to retreat to higher ground as the sea level rises in the next century.

ENDEMISM

The Republic of Palau has approximately 802 native vascular plant species of which 150 are endemic. The rate of endemism for Palau is currently 18.7%, which is slightly higher than the Pohnpei rate of endemism of 16.4% (Lorence & Flynn 2007). This value is based upon a provisional checklist, as a more thorough investigation of Palau's flora is underway (Kitalong et al. 2007). During a 2005 survey of Babeldaob an estimated 54 endemic plants or 37% of known endemics were collected or observed. An average of 27 endemics were recorded within each of 10 geopolitical boundaries or states on the island of Babeldaob. (Each state owns and manages all resources up to 12 miles seaward.) The number of endemic plants found in Babeldaob was greater along the southern part of the island in the states of Airai (34), Ngchesar (33), Ngaremlengui (33), Ngardmau (30), Ngatpang (30), Aimeliik (29), Melekeok (29) than in the northern portion (Ngiwal (22), Ngaraard (22), and Ngarchelong (5).

Plants restricted to limestone substrate were found in the southeastern State of Airai, the only state of Babeldaob with limestone substrate and where limestone islands are only accessible by boat. Southeastern Babeldaob (Ngchesar and parts of Airai) are thought have been the least impacted by human activities in the past (J. Liston, pers. comm. 2007). Northern Babeldaob is considered the most impacted by people in the past. Recent archeological surveys of Ngiwal suggest that an estimated 80% of the land was altered by people over time (Rita Olsudong pers.comm. 2007). Area is also an important factor as Ngarchelong (10 km^2) and Ngiwal (26 km^2) have the smallest land area compared to other States. Greater endemism tended to be found in states with both volcanic and limestone soils, less human disturbance, larger area and less accessible upper watersheds with major river systems. These protected watersheds would have surface or subsurface water during severe droughts and be more sheltered from storms. More survey work is needed to determine if there is a significant difference in the distribution of endemics in Babeldaob.

During the 2004-2005 Babeldaob survey, seven species of rare endemic orchids were found along with several species of rare or uncommon trees. The endemic tree, *Terminalia crassipes* was found along the rivers of Ngatpang, Ngchesar and Melekeok. A stand of *T. crassipes* was also found along a river of Airai's upper watershed in 2007 (Kitalong pers. obs. 2007). A small population of *Parkia parvifoliola* was found in central Babeldaob at Ngaremlengui and one tree was found in Ngiwal and Ngchesar. Other less common endemic plants recorded in southern Babeldaob included *Rauvolfia insularis*, *Diospyros ferrea* var. *palauensis*, *Cyrtandra palawensis*, *Manilkara udoido* and *Myrsine* *palauensis*. Seven of 18 endemic species are restricted to the limestone forests of Palau and were only found southeast Babeldaob including the palm, *Hydriastele palauensis*, the orchids *Cyclopeltis kingi* and *Malaxis calcarea*, the trees *Garcinia rumiyo* var. *calcicola*, *Maesa palauensis*,and *Melicope palawensis* and the vine, *Peperomia palauensis* C. DC. var. *palauensis*. *Goniothalmus carolinensis* was found in volcanic areas of Airai and Ngchesar but is more common in limestone forests.

Reconnaissance surveys over larger areas are needed to better understand the distribution and abundance of less common plant species in Palau. One of the largest endemic trees in Palau is *Serianthes kanehirae* Fosb.var. *kanehirae* which grows on volcanic and limestone islands. This tree was uncommon in the 1988 and 2005 surveys and not recorded in the 2007 survey. *Parkia parvifoliola*, *Terminalia crassipes* and *Rauvolfia insularis* were not recorded in either the 1988 or 2007 surveys. It is important to protect the habitats of less common trees and initiate propagation and replanting. *Serianthes kanehirae* Fosb. var. *kanehirae* is currently being propagated and used to landscape degraded areas in Melekeok. One sapling was planted at the Belau National Museum Botanical Garden and flowered within 2 years. The rare and endangered endemic *Serianthes nelsonii* of Guam and Rota is currently being propagated (Wiles et al. 1996).

FLOWERING AND FRUITING PERIODS

Borchert et al. (2005) documented photoperiodic induction of synchronous flowering near the equator showing that peak flowering occurred during the two distinct annual maxima of insolation corresponding to the equinoxes during March and April and September and October. Corals in Palau exhibit a synchronous spawning that peaks in April (Penland et al. 2004). Since 2003, most of the plants investigated either have year round flowering and fruiting or a peak during the spring and fall, and several had synchronous flowering in the spring (Table 1). Several species have more restricted seasons that overlap over the year, *Pandanus tectorius* reproduces year round with a peak in the spring. *Symplocos racemosa* var. *palauensis* flowers from February to July with a peak during March and bears fruit from June to September. *Maranthes corymbosa* flowers during April and May and bears mature fruit from July to August. *Alphitonia carolinensis* blossomed in synchrony throughout Babeldaob in May and bears mature black fruit from August to November. *Rhus taitensis* flowers in synchrony in July and August and bears ripe fruits from August to October. *Eleaocarpus joga* flowers in May and from September to November and bears ripe fruits in June, July and November. *Pouteria obovata* bears short lived flowers in March, October and November and bears mature black fruits in August and September. *Serianthes kanehirae* Fosb. var. *kanehirae* flowers and fruits year-round. Some plants like *Phaleria nisidai* blossom and fruit 1 to 2 days before new moon and during full moon. These dominant and less common species provide a regular supply of flower nectar and fruits for birds and wildlife.

Trees and shrubs that flower and fruit year round have a greater chance of survival than plants with more restricted flowering periods. Yet, February, March and April are the driest months of the year, a time when pollination would be more likely to succeed. Wet conditions would tend to hinder the movement of pollinators and the dispersal of wind-pollinated species. Fruits in turn may grow more rapidly during periods of rain. Trees with more restricted periods of reproduction may be more vulnerable if the climate changes. The rare *Parkia parvifoliola* was observed with flowers and fruits in May, October and November. More observations are needed to determine relationships between flowering and fruiting and climate. Flowering and fruiting may vary when there are unusual events like severe storms or droughts.

FRUIT MORPHOLOGY

In several families, the native species within a genus have larger fruits than the endemic species. *Calophyllum inophyllum* has a larger seed diameter (3-4 cm) than the endemic *Calophyllum pelewensis* (1.5-2 cm) of the interior lowland watershed and *Calophyllum soulattri* (0.6-0.7 cm) found in the limestone habitats. *Terminalia catappa* has a larger globose fruit (3-5 cm) than *Terminalia samoensis* (1.5-2.5 cm) a smaller shrub found on atolls and exposed habitats of limestone islands. The endemic *Terminalia crassipes* is a large tree found in the upper watersheds along rivers where the exocarp has been modified into a thin light membrane (3.0-3.5 cm). The syncarps for the native *Pandanus tectorius* (24 cm) and *Pandanus dubius* (30 cm) are larger than the endemic *Pandanus macrojeanneretia* (5-6 cm) and endemic *Pandanus aimiriikensis* (6-7 cm). The native *Horsfieldia irya* is restricted to swamp or riverine habitats and has a larger fruit (3-3.4 cm) than the common endemic *Horsfieldia palauensis* (2.8-3 cm). The common *Morinda citrifolia* has a larger fruit (2-3.5 cm) than either the endemic *Morinda pedunculata* (1.5-2 cm) or the endemic *Morinda latibractea* (1-1.5 cm). The latter species has an enlarged white bract and is restricted to the limestone islands. The endemic *Garcinia matsudai* that is found in volcanic soils has larger seeds (3-4.5 cm) than the endemic *Garcinia rumiyo* var. *calcicola* (1.5-2.0 cm) found in limestone soil. The native palm *Pinanga insignis* found in lowland forests has a larger seed (0.9-1.3 cm) than the endemic *Hydriastele palauensis* (0.5-0.6 cm) in the limestone forests. Other variations in fruit morphology occur such as for the large uncommon endemic tree *Serianthes kanehirae* Fosb. var. *kanehirae* that has a woody fibrous pod that is 10-17 cm long with 2 to 7 small hard seeds. The rare endemic *Parkia parvifoliola* has a strap shaped fibrous pod 24-30 cm long. These two trees are nitrogen fixers and can therefore grow in nitrogen poor soils. The thick fibrous pods can lie dormant until soil conditions are more suitable for growth. The common endemic *Trichospermum ledermannii* has capsules filled with small (2 mm) hairy seeds that readily disperse with the wind. *Horsfieldia* spp. and *Casearia hirtella* have hard fibrous exocarps that protect the seeds.

Small sized and light weighted fruit or seeds may be adaptations to either conserve energy when environmental conditions are less than optimal or to reallocate energy into the production of numerous smaller fruits or seeds that can readily disperse by air and increase their probability of survival. Protective thick capsules and fibrous pods may be adaptations for fruits to protect their seeds for a longer period of time and enable them to remain dormant until environmental conditions improve. Large buoyant seeds such as the *Cocos nucifera* either lie dormant or disperse by water over great distances. *Heritiera* seeds have been observed to float along with the keel up serving as a sail (Falanuruw, pers. comm. 2007). Nitrogen fixing plants in the family Fabaceae can survive in nutrient poor soils. Plant species on small islands are vulnerable to variable environmental conditions. Plants that evolve mechanisms to cope with harsh conditions are more likely to survive than those that do not. Adaptation strategies to survive during periods of severe and frequent droughts, storms, sea level rise, land modification and invasive species exist among the endemic and native species that have either evolved or persisted over time.

INVASIVE SPECIES

Potential threats to the forests include two large invasive trees in the family Fabaceae: *Adenanthera pavonina* and *Falcataria moluccana* originally planted for agricultural purposes (Mayo 1954). These successful invasive trees are members of the Fabaceae family and grow in poor soils because the roots can fix nitrogen. (The Fabaceae Family is the second largest family of plants found in Palau and includes 111 species of which 91 are introduced including 24 invasive species.) *Adenanthera pavonina* was common in Ngarchelong and found in Uruktabel Island, Koror, Melekeok, and Ngatpang. *Falcataria moluccana* was common in Ngaremlengui where it was planted by Japanese farmers as a shade tree for cacao plantations (Kitalong & Holm 2004, Costion & Kitalong 2006). Endress (2002) found that *F. moluccana* dominated early successional forest stands in Ngaremlengui, but was not dominate in mid-successional forests and was not found in mature forests. It is important to monitor this large tree at other study sites to determine if it has become dominant in mature forests in other parts of Babeldaob or if it is excluded by native trees. The native vine, *Merremia peltata* grows rapidly in disturbed or open areas overgrowing and killing trees within 100 m of the national highway. Community clean-ups have been ongoing to control its widespread distribution.

Casaurina equisetifolia is among the most successful colonizers of denuded areas, new surfaces and fresh sand flats. This species has nitrogen-fixing bacterial root nodules and produces carpets of “needles” that exclude other plants. This tree occurs on volcanic and limestone substrate at high and low elevations and on all types of slopes in the Northern Marianas (Mueller-Dombois and Fosberg 1998). *Casaurina* forests covered 451 hectares or 20% of the coral islands of Palau in 1987. Angaur and Peleliu had large stands of this tree as well as the Ngemelis Complex and many rock islands. This tree a successful pioneer species commonly found along shore areas previously or currently used as villages or temporary shelters. Long term monitoring is needed to determine if this tree may be out-competing native rock island trees on some rock islands.

The greater sulphur-crested cockatoo, *Cacatua galerita* was introduced to Palau in the 1940's and has established populations in the limestone islands (Engbring 1988). Cockatoos were rare in the Ngerukuid Preserve as only 2 pairs were reported during the 1988 survey. Cockatoos feed on the hearts of endemic palm, *Hydriastele palauensis* and are responsible for killing large stands of these trees. An estimated 5% of the trees surveyed in the Preserve were *H. palauensis* at risk, and the effects of cockatoos on this palm should be reassessed. It was recommended that seeds of this palm be collected for propagation (Birkeland and Manner 1989). The cockatoo has expanded into Babeldaob and its impact on native trees in Babeldaob also needs to be assessed.

Discussion

FUTURE RESEARCH AND RECOMMENDATIONS

Effective conservation is a challenge as populations grow, resources become scarce, imported resources are substituted for local resources, technology improves and habitats become more accessible (Smith et al. 2000). On October 1, 2007, the 53 mile (83 km) national highway was officially completed in Babeldaob, Palau's largest island. Secondary impacts have begun with chronic incremental loss of forests for new homes and infrastructure. Previously inaccessible upper watersheds with old growth forests and swamp forests are now vulnerable. Ongoing clearing of limestone and volcanic forests, burning and clearing of savanna and clearing and filling of wetlands and mangroves is causing the loss of plants and potentially impacting the terrestrial species dependent upon them. Long term studies are needed to determine the impacts and the resilience of Palau's forests to disturbances caused by fires, land clearing, typhoons and invasive species. The dynamics of forest growth and loss need to be studied at different temporal and spatial scales. Permanent plots need to be established and existing survey plots mapped and locations shared. Existing data on forests plots needs to be archived and retrievable for future planning, forest management and protection. Floristic studies need to be expanded within Babeldaob and to the other States of Palau. Focused studies on rare endemic tree species such as *Parkia parvifoliola* are needed. A study on pollination and seed dispersal of endemic plants by insects, birds and bats is needed. The fruit bat, *Pteropus mariannus pelewensis* is an endemic subspecies, known to feed upon the nectar and fruits of 67 plant species representing 35 families of which 11 are endemic trees (Wiles et al. 1997). The distribution of invasive tree species such as *Falcataria moluccana*, *Adenanthera pavonina* and other invasive species need to be mapped, monitored and effectively controlled.

Educational programs that build upon traditional ecological knowledge are critically needed. Integrative agroforestry with both native and introduced species has worked for centuries in Palau. Customary tenure systems and practices require ongoing support in combination with the protection of a network of important forest areas. One goal of existing programs is to rehabilitate areas with highly eroding soils through the propagation and planting of native plants. The Ngerikiil Watershed is the most populated watershed in Babeldaob with growing urban development and subsequent erosion and sedimentation. Other watersheds are facing similar problems as development expands on both private and public lands throughout Palau. Community driven programs require ongoing technical and financial support. People in communities within watersheds must cross geo-political boundaries to effectively manage their terrestrial ecosystems. The Babeldaob Watershed Alliance initiative is taking the necessary steps to make this happen. Effective coordination and information exchange between national, state, non-government and communities is an ongoing challenge. A shared vision with island-focused land use policies, applied research and educational programs will ensure that Palau's forests will remain intact into the next century.

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