Chapter 3
Island Structure and Resource Systems

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Chapter 3

Island Structure and Resource Systems

ISLAND FORMATION

Islands in tropical waters of the Pacific Ocean and the Caribbean Sea commonly bring to mind only white sandy beaches backed with a fringe of coconut palm trees. Yet, a close examination of the form and geology of the islands shows that major differences exist between island types that significantly affect opportunities for renewable resource management and development. These fundamental differences play an important role in determining what kinds of technologies can be applied that are likely to prove productive for island residents over the long term and which others, though perhaps leading to short-term gains, ultimately may produce long-lasting adverse impacts on the island resource base—the soil, water, vegetation, and wildlife.

Details of the geologic formation of the islands are beyond the scope of this assessment. Nevertheless, a simple fourfold classification of island types based on their geology should assist the reader in assessing potential impacts to an island's environment from proposed technological applications. In addition, it should help to improve understanding of why islanders, past and present, have chosen particular methods of resource use.

Although many of the islands' origins relate largely to volcanic processes, their name classification only partly reflects this. The four categories of islands used in this assessment are: high volcanic islands, atolls and low coral islands, raised limestone islands, and continental islands.

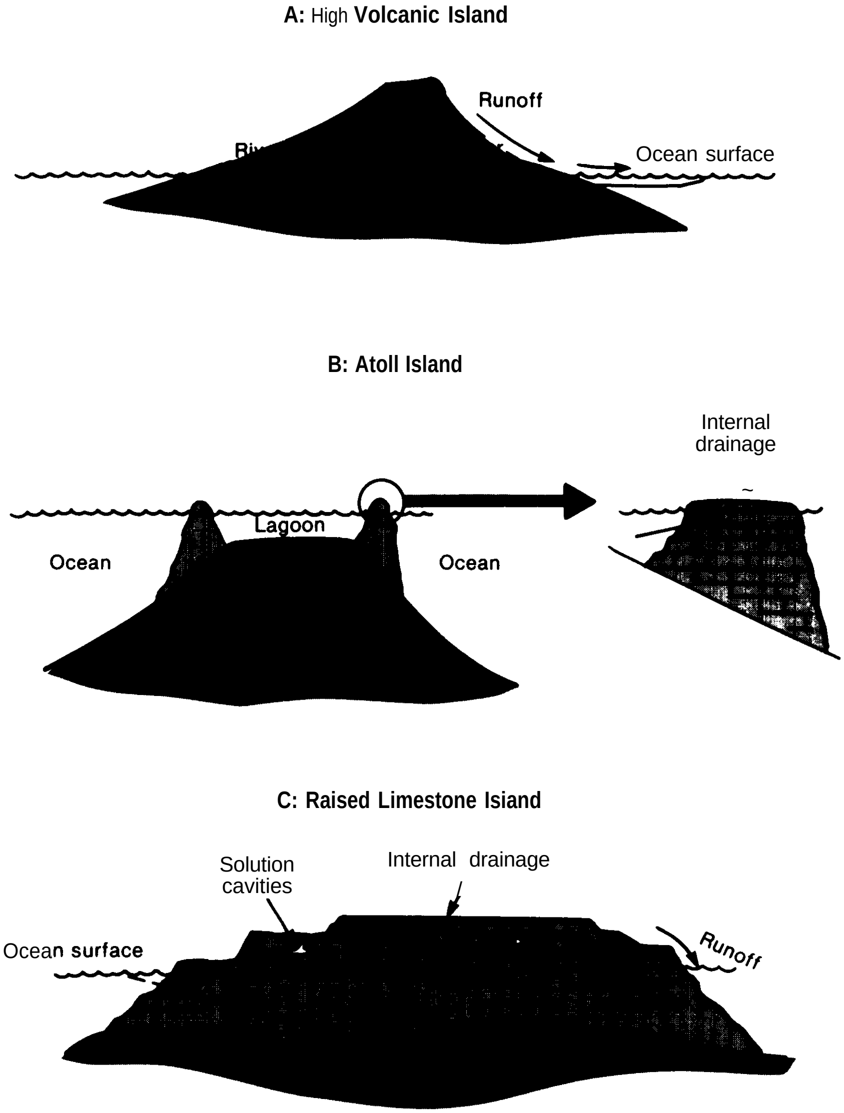
High Volcanic Islands

High volcanic islands are the cone-shaped peaks of volcanoes (perhaps 1,000 feet or more in altitude) that extend upward from the ocean floor. The conical shape is preserved best on young volcanic islands; older islands become deeply incised with stream valleys because of erosion from running water (figure 3-1 (A)). Some volcanoes are still active such as Pagan Island in the Northern Mariana Islands; some are dormant such as Sariguan in the Northern Mariana Islands; and others are extinct such as Pohnpei or Kosrae. Measured from the sea floor to the island summits, these volcanoes represent some of the highest mountains in the world. The predominant rock forming the volcanic islands is basalt, a dark-colored igneous rock rich in minerals containing silicon, aluminum, calcium, magnesium, and iron as dominant elements.

Once volcanoes reach the ocean's surface, marine organisms like corals, algae, and sponges start to grow and reproduce on the bottom of the sunlit, warm nearshore waters that surround the new island. In the early stages of growth, the marine organisms of the colony grow on one another until they reach the surface of the water. Coral structures that are close to the island (generally within one-quarter of a mile from shore) and often surround it, are called fringing reefs. Such reefs may become barrier reefs if the central island begins to submerge. Barrier reefs generally are 1 to 5 miles offshore and are separated from the island by a lagoon which is relatively deep (60 to 300 feet) (40).

Many volcanic islands over geologic time have slowly subsided beneath the ocean surface. The living marine organisms of the surrounding reefs in many cases have been able to grow rapidly enough to keep their surfaces at or near sea level, thus offsetting the rate at which the volcanic island subsides. Through this process, the reefs can maintain their existence even when the enclosed island gradually sinks below the ocean's surface. With the disappearance of the central island, the ringlike reef complex then becomes an atoll.

Figure 3-1 .—Depiction of Island Types



SOURCE: Office of Technology Assessment, 1986

Atoll Islands

Atolls are low-lying, narrow, ring-like coral reefs composed of highly permeable coralline limestone (calcium carbonate) derived from the remains of marine reef organisms. Individual atoll islands occur as part of the atoll reef and rise only a few "feet to a few tens of feet above mean high tide. For example, the highest point in the Marshall Islands is 25 feet above sea level on Likiep Atoll (40). Atolls enclose a lagoon of several feet to several hundred feet in depth. Submarine landslides, wave action, currents, tides, and storms commonly produce or maintain breaks in the atoll thereby providing boats or ships with passages connecting the open sea with the shallow lagoon (figure 3-I (B)).

Growth of atoll reefs is greatest on their windward sides where the food supply is highest for reef organisms. Storm and wave action carry reef or atoll fragments into the atoll's lagoon and pile them on the reef above the water level to form islands. This sediment source keeps the waters of the atoll's lagoon shallow.

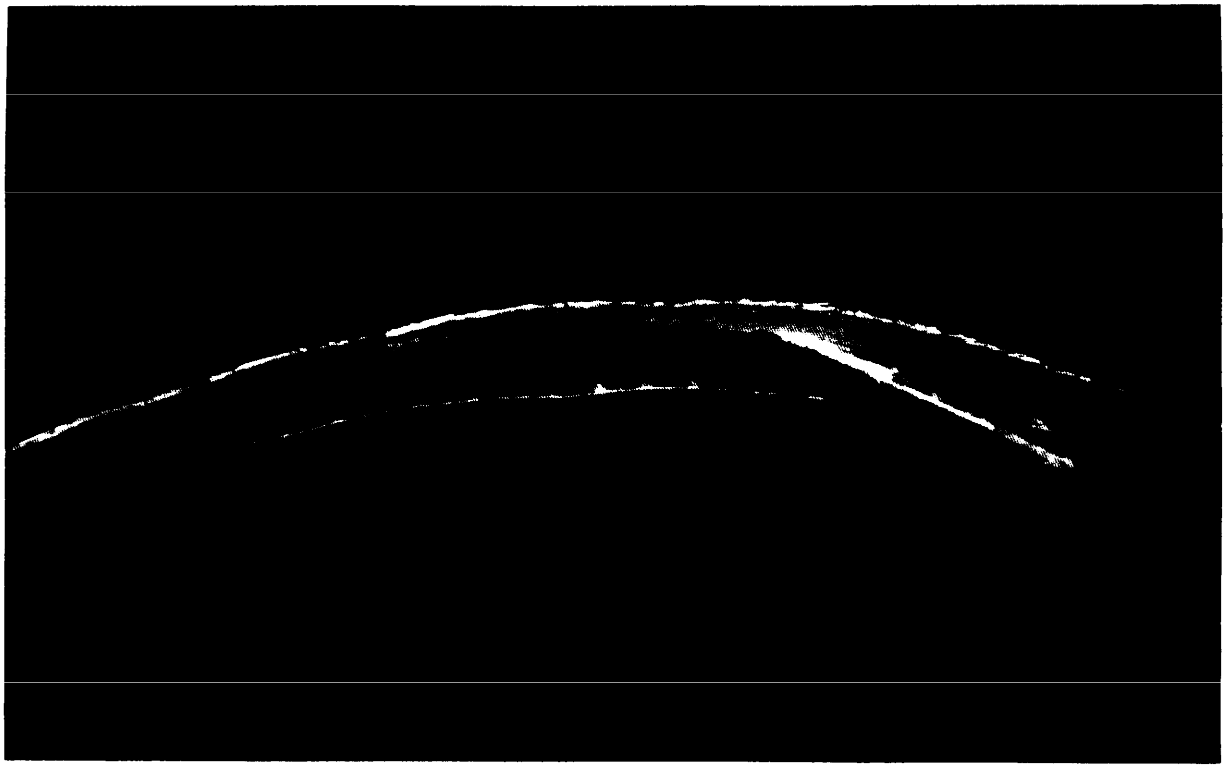


Photo credit: Office of Technology Assessment

A low-lying atoll island in the Marshall Islands, built on the inside edge of an encircling coral reef.

Some low coral islands in Micronesia form on top of coral pinnacles and are not associated with lagoons. These islands, such as Nama and Kili, otherwise resemble atoll islands.

Raised Limestone Islands

Raised limestone islands consist of nearly horizontal beds of coralline limestone that originally were formed in the waters surrounding older volcanic islands. Over geologic time, the marine limestone beds have been raised above sea level by upward moving volcanic islands, or by lowering of the sea level. The extensive uplifted limestone beds of Guam, for example, now reach about 500 feet above the sea surface. Many such islands have prominent wave-cut terraces carved into the limestone layers indicating times during the Pleistocene ice age when the sea level was different than it is today, times when continental glacial ice sheets in regions closer to the poles were thicker or thinner.

Because of their origin, raised limestone islands may contain exposed land surfaces of older volcanic rocks. Like high volcanic islands, they are also likely to have fringing reefs along their coasts.

The porous limestone layers are composed mostly of calcium carbonate which dissolves over time as plentiful tropical rainfall moves downward through the permeable beds. Solution cavities like sinkholes and caves result (figure 3-1 (C)).

Continental Islands

Continental islands are extensions of continents or of certain undersea mountain ranges. The rocks comprising such islands are of a much wider variety than those of the other island types and signify a more complex geological history. Puerto Rico and the U.S. Virgin Islands, for example, are part of the Antilles, a sea-floor mountain range geologically associated with the structure of the extreme southeastern part of the United States. Similarly, Palau is the surface expression of the eastern extremity of a continental-type mountain range running-from west to east in Indonesia.

Continental islands do not have a characteristic form. They may, however, have a border of fringing reefs or lagoons with barrier reefs like those of high volcanic islands and raised limestone islands.

PREVAILING CLIMATE

Introduction

The majority of the U.S.-affiliated islands lie in the Northern Hemisphere, with American Samoa being the only U.S. Territory in the Southern Hemisphere. All of the islands are within the tropical marine climatic region, between the Equator and 23.5° north/south latitude. Weather changes in tropical climates are complex and may occur frequently(4). Further, considerable climatic differences may exist between island areas. Differences in the amount and seasonality of rainfall, wind, and tidal conditions exist throughout the Pacific and Caribbean area. While tropical climates are characterized by warm, often wet, fair weather, they are equally known for producing major disturbances such as cyclonic storms.[1]

Overall weather patterns may be predictable (e.g., temperature, rainy seasons, tropical storm seasons, and afternoon rainstorms), however, tropical weather also may be highly variable. The high level of solar radiation received by tropical areas gives rise to this variability. High energy levels may allow the rapid formation of storm systems and sudden rainfall, and may also affect wind patterns and occasionally ocean currents. The high energy level of tropical air masses means that even small trigger mechanisms may produce disturbances (4).

The action of the ocean may compound impacts of sudden storm system formations. The ocean also may serve to transfer impacts of weather or other natural events such as earthquakes to islands some distance from the source of the disturbance. The small size and isolation of islands increases their vulnerability to disturbances, however, their existence indicates that these areas possess a highly effective capacity for recovery.

1The term cyclonic storms will be used in this text to cover such weather formations as typhoons and hurricanes.

Winds

The northeast and southeast tradewinds prevail upon the U.S.-affiliated tropical islands. The tradewinds converge in the equatorial trough of low pressure forming what is known as the Intertropical Convergence Zone (ITCZ) [4). The low pressure of this area gives rise to the sporadic cloudiness and frequent rainfall associated with tropical regions. The ITCZ shifts during the year accompanied by seasonal changes in the direction and intensity of the winds. For example, the islands in the Caribbean experience relatively consistent winds year round; however, the direction changes from a slightly stronger northeast wind during winter months to a southeast wind during summer months. Guam experiences a similar seasonal wind shift, receiving the strongest winds during winter months. American Samoa, in the southern hemisphere, also experiences seasonality in winds, receiving the southeast tradewinds with relative consistency for 9 months of the year (46). The Northern Mariana Islands receive strong northeast tradewinds for 9 months of the year, November through June, while July through October is marked by more variable winds. These islands also lie on the eastern fringe of the Asiatic monsoon circulation system (47).

Precipitation

Precipitation levels in the tropical climatic region generally are high, however, variations

Box 3-A.—General Characteristics of Tropical Climates

- **High humidity except in arid regions.** Humidity is driven by high levels of insolation in tropical regions, coupled with large areas of freely evaporating surface (oceans), generally constant winds help transfer water vapor from ocean surface to atmosphere and ensure a continuous supply of unsaturated air,
- **Cloudiness commensurate with humidity.** Cloudiness associated with tropical regions generally is a function of the atmospheric moisture levels in combination with the high insolation levels which encourage uplift of air. Topographic barriers also may cause cloud formation by forcing moisture laden air high enough to reach the lifting condensation level.
- **Small seasonal temperature variation; diurnal variations often greater than seasonal.** Temperature in tropical regions generally fluctuates around the low 80s Fahrenheit year round. This is caused by the high, and generally stable, levels of insolation received, combined with the moderating effect of the ocean. As a result diurnal temperature fluctuations are generally greater than seasonal variations.
- **Annual rainfall ranges from 80 inches or greater in wet environments to less than 10 inches in arid environments.** Precipitation is a function of atmospheric moisture [illegible]

exist among islands (table 3-1). Variation also may exist in the geographic distribution of precipitation on a single island. The variation in rainfall amounts among island areas largely is attributable to topographical differences, island size, and geographic location. Generally, as latitude increases rainfall patterns become more seasonal, with annually occurring dry periods. The seasonality of rainfall patterns is attributed, at least in part, to the shifting of the ITCZ and the associated change in the moisture content of the atmosphere in relation to island location. High islands generally receive larger levels of rainfall due to an orographic effect; air is forced up and over a topographic feature causing condensation of atmospheric moisture and gener-

Table 3-1.—Mean Annual Precipitation Level and Temperatures

Polity/island	Latitude	Mean annual rainfall (inches)
Puerto Rico	18° N[a]	40-200[a]
U.S. Virgin Islands	18° N[a]	40- 60[a f]
American Samoa	14° S[e]	I00-200[b]
Guam	13° N[e]	80- 95[c]
Northern Mariana Islands	14° N 20.5° N[e]	75-121[d]
Marshall Islands	5° N 12° N[e]	135[g] (Majuro)
Federated States of Micronesia:		
Kosrae	5° ***30' N***[e]	227[g]
Pohnpei	7° N[e]	190[g]
Truk	5°-7° N[e]	139[g]
Yap	6°-12° N[e]	122[g]
Palau	7° 30' N[e]	147[g]

SOURCES:
[a] D. Smedley, Climates *of the States: Puerto Rico and U.S. Virgin Islands,* U.S. Department of Commerce, Weather Bureau, Climatography of the United States No. 60-52 (Washington, DC: U.S. Government Printing Office, 1961).
[b] U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of Coastal Zone Management, *American Samoa Coastal* Manage*ment Program and Final Environmental Impact Statement,* 1980.
[c] U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of Coastal Zone Management, *Guam* Coastal *Management Program and Final Environmental Impect Statement, vol.* 1, 1979.
[d] U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of Coastal Zone Management, *Commonwealth of the Northern Mariana Islands* Coastal *Resources Management Program and Final Environmental Impact Statement,* 1980.
[e] J.E. Maragos, "Coastal Resource Development and Management in the U.S. Pacific Islands," OTA commissioned paper, Washington, DC, 1986.
[f] Caribbean Research Institute, *Waterplan:A Comprehensive Water Management Framework* for the U.S. *Virgin* Islands, *Virgin Islands Water Resources Center,* June, 1979.
[g] National Center for Atmospheric Research (NCAR) Boulder, CO, rainfall data—measured at one location for each island area—does not reflect variation in geographic distribution.

ally precipitation. Islands of lower altitude depend in part on the convective force of the air over the island to promote rainfall; the moist air is heated over the island and rises to a point at which condensation occurs.

Guam and the Western Caroline islands of Yap and Palau are subject to a monsoon-like pattern with dry spells often occurring between December and June (15). Other islands such as Pohnpei experience less variation in rainfall patterns, receiving generally stable amounts throughout the year. High average rainfall in the central Carolines (100 to 130 inches/year) promotes lush vegetation. On coral islands the rainfall partially compensates for the inherent small freshwater storage capacity (2,40).

Considerable variation in precipitation regimes exist between Puerto Rico and the USVI, despite their proximity. Puerto Rico receives a mean annual rainfall of 65 to 70 inches, while the USVI recieves a mean annual amount of approximately 40 inches. The topographic features of Puerto Rico, larger land mass and mountain peaks in excess of 4,000 feet, promote both convective and orographic precipitation. These features contribute to Puerto Rico's significant variation in the geographic distribution of precipitation that gives rise to a number of different environments ranging from a tropical rainforest (Luquillo) to an arid southwest coast. Although the USVI receives both orographic and convective stimulated precipitation, the much smaller land area and lower elevations result in a less marked variation in precipitation distribution. Both island areas experience a relatively dry season that generally occurs between December and April.

Temperature

Island climates are strongly influenced by the persistently high levels of solar radiation received throughout the year as well as by the tempering effect of the surrounding ocean waters. The ocean acts as a heat sink/source to regulate temperature variation through the year. During warmer seasons the ocean retains energy and during the cooler seasons is able to release energy, resulting in relatively little seasonal temperature fluctuation. Diurnal temperature changes commonly are greater than those experienced from one season to the next (29).

Disturbances

The major climatic disturbances associated with the island areas take the form of cyclonic storms. Cyclonic storms, which severely affect Puerto Rico and the USVI, generally develop over the southern North Atlantic Ocean east of the Lesser Antilles (4,36). Those most affecting Micronesia originate in the central tropical Pacific Ocean (4). Prediction of cyclone paths can prove difficult because of the variability of wind patterns in the tropical region. The Caribbean islands generally receive fewer cyclonic storms than the Pacific islands north of the Equator, which lie in a major path of cyclonic storms (4). Tropical cyclones are frequent events in the Mariana and Western Caroline Islands of Yap and Truk (24), but less common in the Eastern Carolines, the Marshalls, and American Samoa (7,13). Cyclonic storms are not considered a severe problem on Pohnpei, although four cyclonic storms have hit the island in this century, most recently in May of 1986.

Satellite image courtesy of C. Wahle

Cyclonic storms are relatively frequent events for many U.S.-affiliated islands and often cause severe damage to island populations and ecosystems.

Cyclonic storms develop from tropical depressions when pressure and temperature conditions are favorable. These storms may produce winds of 60 to 200 miles per hour and generally are accompanied by heavy rainfall and thunderstorms. The storm is generated by the release of energy through massive condensation of water vapor. The bodies of water surrounding the tropical areas experience their highest temperatures in the late summer months providing the energy levels necessary for the generation of a cyclonic storm (30). Thus, such disturbances generally occur during late summer and autumn when the ITCZ is shifting towards land south of the Equator. However, exceptions do occur. For example, on Yap, cyclonic storms are most frequent during the transitional months (particularly November) when the tradewinds are returning. Cyclonic storms that pass quite near or over an island can cause severe destruction. The high winds and torrential rainfall may cause wind damage, flooding, landslides, and loss of life. Puerto Rico was severely damaged by a cyclonic storm in 1928; the vortex of the storm moved southeast to northwest affecting the entire island.

Cyclonic storms may have both primary and secondary effects on the island ecosystem. Primary effects include physical damage to the reef and shore areas and land erosion. High winds and torrential rainfall may cause destruction on land. Storm wave assault may cause coastal erosion, fragmentation of corals, slumping of reef framework, and abrasion and scouring of the reef (39). Secondary effects include the loss of biota dependent on the physically damaged systems (55). Structural damage to the reef framework was minimal after Typhoon Pamela passed Guam in 1976, but damage to living coral and algal communities was intense and widespread on the deeper forereef slope zone (13). Recovery of the affected ecosystems generally is slow because the base from which to build is so small (9).

A less common but equally destructive disturbance of tropical oceans is the tsunami. Tsunamis, also known as seismic sea waves, may be produced by earthquakes, landslides, or volcanic eruptions on the ocean floor and may reach velocities of up to 500 mph and heights of up to 115 feet as they hit the shoreline. Both the Pacific and Caribbean U. S.-affiliated islands are located in seismically active areas. The Pacific Ocean is ringed with earthquake-producing trenches and active volcanic areas. However, the deep waters surrounding the islands preclude major disruption by tsunamis (39). The narrow continental shelf structure of the Caribbean islands generally does not allow the tsunami to build sufficient height to cause major disruption. However, the tsunami remains a potential hazard for islands.

ISLAND HYDROLOGY

Many tropical islands receive high levels of rainfall annually; some, however, exhibit semiarid conditions. Even with high levels of rainfall, islands are not necessarily exempt from surface and groundwater shortages. An island's topography and geology largely determine where rainfall will accumulate and how long it will remain available.

The fundamental, unifying concept in understanding water movement in islands is the hydrologic cycle (figure 3-2). The cycle is a dynamic, conceptual model that relates the continuous movement of water through the vapor and liquid phases. The components of the hydrologic cycle important to tropical islands are:

- Precipitation: Water added to an island's surface from the atmosphere (e.g., rain, fog, and dew).
- Evaporation: The process by which water is changed into vapor. In the context of the hydrologic cycle, the most important form of evaporation in a quantitative sense is that from the seas and oceans. Its return as precipitation is the main source of water for islands. Because islands surfaces are

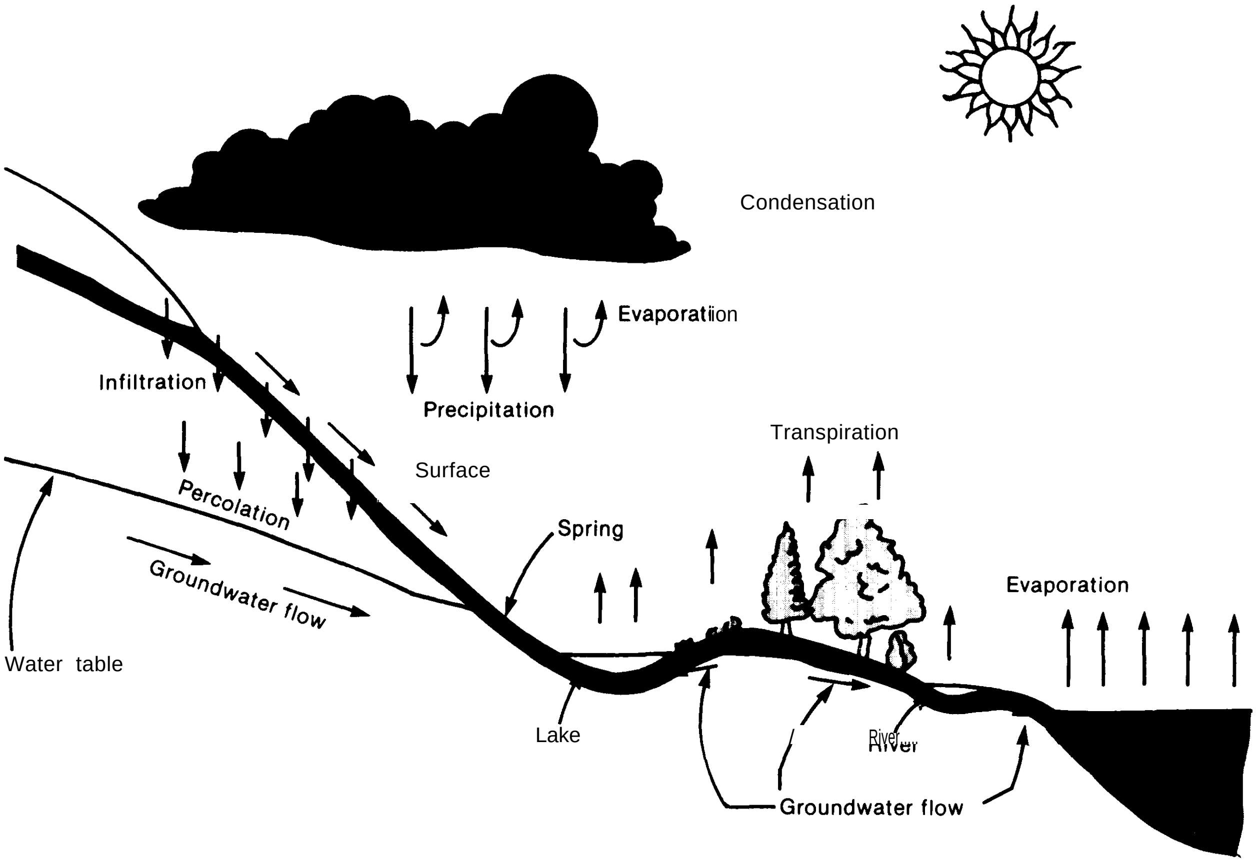
small in comparison to the ocean surface, evaporation from islands contributes a small part to overall precipitation.

- Transpiration: The process by which water passes through a living plant and enters the atmosphere as vapor.
- Infiltration: The process whereby water soaks into the soil layers.
- Percolation: The downward flow of water through soil and permeable rock formations to the water table.
- Runoff: The portion of precipitation that flows downhill on the island's surface to reservoirs and catchments and ultimately to the ocean (l).
- Retention: The proportion of water that is held in the substrate after recharge and transpiration.

The Sun is the driving force behind the hydrological cycle. It causes the evaporation of water from the ocean surface. The water vapor may condense to form clouds and ultimately return to the Earth's surface as precipitation. Some precipitation evaporates again as it falls.

Water reaching the surface of a watershed—the fundamental geographic unit of hydrology where an area of geographically low land is partly surrounded by relatively higher lands—may follow one of four courses. First, it may remain on the surface as pools or as surface moisture that evaporates back into the atmosphere. Second, precipitation reaching the ground may flow over the surface into depressions and channels to become surface runoff in the form of streams. Surface runoff expressed

Figure 3.2.—The Hydrologic Cycle



Water passes continuously through this cycle from evaporation from the oceans into the atmosphere through precipitation onto the islands and eventual runoff into the oceans. Human use of water may modify this cycle at virtually every point.

SOURCE: H Hengeveld and C. DeVocht, *Urban Ecology* **6(1-4):19, 1982.**

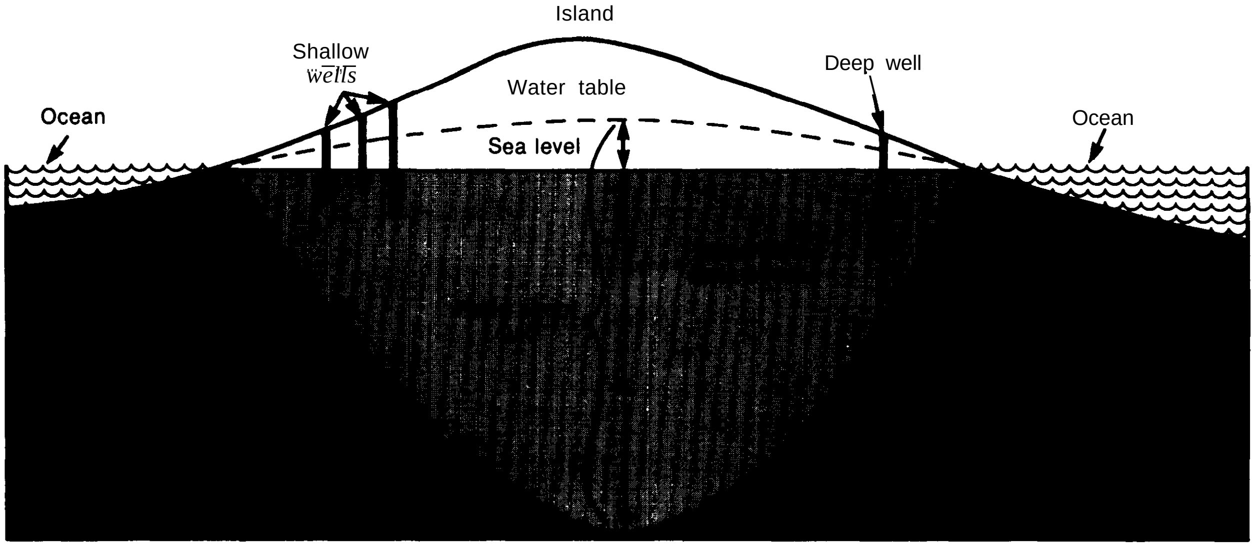
as rivers or streams, generally occurs only after evapotranspiration and soil and groundwater recharge have been satisfied or when precipitation is heavy. Third, precipitation may infiltrate the land's surface directly and percolate downward to groundwater where it may be stored. Fourth, it may recharge the soil and be partly recycled through evapotranspiration.[2] Shallow groundwater can move upward to the soil surface and plant root zone by capillary action where it is taken up by plants and transpired, or it can move laterally until it intersects the land's surface as a spring, or by underground flow into streams, ponds, or the ocean.

The amount of rainfall that can infiltrate the soil is determined largely by the permeability of soil (governed by the size and interconnectiveness of the spaces within the soil or rock layers) and the amount of water already present in those spaces. For most soils, infiltration rates are highest at the beginning of a rainstorm when the soil is dryest, gradually decreasing with time. Some infiltrated water will be retained near the surface by capillary forces. Where percolation and/or infiltration rates are high relative to annual precipitation, no runoff will take place (e.g., sandy, calcareous soils). Commonly, the water will percolate downward where it will enter into groundwater storage.

Water that exists below the surface of the Earth in interconnected openings of soil or rock

[2]The combined processes of evaporation of water from the land and vegetation surfaces and transpiration of water vapor through plant leaves.

Figure 3-3.—Ghyben-Herzberg Lens



NOTE: Diagram is vertically exaggerated for Illustrative purposes,

SOURCE: R.J. Ordway, Earth *Science and the Environment (New* York, NY: Van Nostrand, 1974),

is called "subsurface water. " That zone, where the pores of the sediments and rocks are filled with water, is called the groundwater zone. The top surface of this zone is called the water table. Between the water table and the surface of the Earth is the "zone of aeration," where the pores of soil and rock contain some water but less than total saturation. The water table commonly rises and falls with time as the availability of water at the surface changes.

Groundwaters storage beneath oceanic islands has certain special characteristics that differ from continental areas. Fresh water that has percolated downward through the soil to a level below which it saturates all of the interconnected pores and openings in bedrock or in consolidated sediments forms a lens commonly referred to as the Ghyben-Herzberg Lens (figure 3-3). The groundwater table is the top of this lens and is situated above sea level because the fresh water is less dense than the seawater that saturates the rocks below. The groundwater lens extends a greater distance below sea level than above in a manner similar to that of an iceberg. The basal contact of the fresh water with the seawater is transitional. For every 1 foot of groundwater that is situated above sea level, approximately another 40 feet will exist below. Many small, drier islands and atolls may have only a 20:1 ratio, and some may have no fresh water lens (34). Therefore, small changes in the altitude of the groundwater table correspond to large changes in the thickness of the fresh water extending below sea level (32).

The lens tapers from being thickest at the island's center to being thinnest at the island's edge. Close to the shoreline the entire lens may be brackish from tidal induced mixing of seawater and fresh water. As a consequence, salt-tolerant trees commonly grow near an island's edge, above the thinnest part of the freshwater lens, and salt-intolerant trees, like breadfruit, grow better toward the center of atolls (40).

High Volcanic Islands

Basaltic rocks forming the main part of high volcanic islands may be quite permeable because of the numerous joints, cracks, and bedding planes they contain (35). Consequently, precipitation can be trapped quickly by these

[3]While the term groundwater covers all subterranean water, fresh, brackish or saline, the groundwater that is most limiting in the island context is fresh water and thus is the focus of interest.

Photo credit: A. Vargo

The steep slopes of high volcanic islands, such as American Samoa, predispose island communities to flood and landslide hazards.

rocks and a thin soil cover. Nevertheless, during heavy rainstorms, large amounts of water still run off such islands quickly because of the generally steep slopes, the small size of watersheds, and sometimes because of the small total amount of water storage space in the rocks. Large amounts of erosion are common in such situations. Flash flooding from high rainfall of short duration flowing through narrow stream valleys often is a serious problem.

High islands that are either active or dormant volcanoes may emit some of the groundwater as steam and water vapor at holes or fissures called fumaroles. Groundwater in contact with rocks having elevated temperatures is likely to contain large amounts of dissolved solids that commonly precipitate around hot springs (32).

Atolls

Coralline limestone atoll islands and low coral islands are highly permeable and, thus, readily accept heavy rainfall. Most atolls rise only a few feet to a few tens of feet above mean high tide and, because of their narrow dimensions, the groundwater lens beneath them is not large. Storms can drive saltwater onto and over some atolls thereby contaminating the fresh groundwater lens with seawater. Salt carried in sea spray can build up in atoll soils, but where rainfall is heavy over short periods of time salt will be flushed from the soil (40).

Raised Limestone Islands

Raised limestone islands are lithologically similar to atolls in composition and permeability. Raised limestone islands generally are considerably larger than atolls, thus, the freshwater lens beneath is larger. Precipitation on these raised islands quickly moves downward through the porous rock and along openings formed by solution along joints and bedding planes. The vertical distance from the land's surface of raised limestone islands to the water table may be as much as several hundred feet depending on the island's elevation. Contamination of the fresh groundwater lens by seawater is most likely to be limited to nearshore areas affected by storm surges.

Natural surface-water supplies from streams and ponds are sparse on limestone islands because of the rock's high permeability. However, springs may occur along the shore near sea level where the groundwater flows laterally into the sea. Larger solution features like caves and sinkholes are common on such islands.

Continental Islands

Continental islands have the most complex hydrologic systems of all the island types because of their complex geologic origin. Groundwater infiltration rates, in general, will be much more variable on continental islands than on volcanic islands, atolls, and raised limestone islands. For example, Puerto Rico is a continental island with a wide variety of rock types, each

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with differing porosity and permeability. It is the composite of these characteristics plus local climatic variations that make up the island's overall hydrologic system. As such, continental island hydrology does not lend itself to a simple description of the sort suitable to other island types.

Some parts of continental islands have a local geology and lithology similar to the other island types. In these cases, the workings of the hydrology will parallel the other island types. Such would be the case for volcanic and limestone terranes. But where terranes of other lithologies exist major differences can occur.

Typically, continental islands have a core of igneous rock with limited aquifer development in the zones of fracture and faulting. Alluvial and limestone deposits commonly occur around the flanks of the island's core to produce coastal plains which may be of considerable size (e.g., Puerto Rico's coastal plain extends nearly 4 miles in width). Rainfall is most plentiful in the mountainous regions and diminishes toward the coast promoting significant variation in precipitation levels between coastal and mountain areas. Major coastal aquifers may exist in some areas, recharged by precipitation on the alluvium as well as by streamflow from upper watersheds (28).

ISLAND SOILS

Soils form from the chemical and physical breakdown of rocks and minerals. Limestone and basalt and the alluvium derived from their erosion constitute a large part of volcanic and limestone islands' surface material, while on continental islands a wider range of rock types exist. Chemical weathering processes predominate where precipitation is high and physical weathering processes predominate where precipitation is low; a continuum exists between the two extremes. Where chemical weathering processes predominate, soils largely are depleted of nutrients regardless of the parent rock type.

Many soils that form in hot, wet tropical areas have significant fertility problems. This is the case for most parts of many Pacific islands and much of Puerto Rico. Under such conditions, chemical weathering of parent rock materials is the predominant soil forming mechanism. High temperatures, high precipitation levels (approximately 50 inches and above) and the action of plant roots combine to accelerate leaching of nutrients from the rock and soil mineral particles, transforming the primary minerals to secondary minerals. The secondary soil minerals are composed largely of aluminum, silicon, iron, oxygen, and water (16). The chemical composition often is imbalance so that many food or tree crops planted on such soils will have limited productivity or will not survive. In some soils, silicon and iron concentrations are so low, and aluminum so high that the composition of bauxite, an aluminum ore, is approached or reached.

On islands where the annual rainfall is lower (southwestern Puerto Rico and much of the Virgin Islands) and where the temperature generally remains high year-round (average of 800 to 850 F), physical breakdown of rocks and soil minerals plays an increasingly larger role in soil formation. In this process, the particles become smaller but their chemical composition is less affected and leaching of soil nutrients is more limited. Physical disintegration can occur in a number of ways; for instance, salts and certain minerals in small cracks in rocks and soil particles expand when wet (hydration) and contract when dry (dehydration), thus causing grains to break (5). And, of course, the growth of plant roots is a powerful agent in breaking up rock and soil particles.

In drier areas where rainfall is seasonal, nutrients needed by many plants commonly are in the soil but become available to the plants only if sufficient water is available (6). If most of the water evaporates from the soil surface rather than percolating downward into the soil, dissolved solids or salts can accumulate as

Box 3-C.—Common Characteristics of Island Soils

- Most island soils, where annual rainfall exceeds 50 inches, largely are depleted of nutrients [illegible] warm, moist climates, plants roots and [illegible] and soil [illegible].
- In drier island areas, such as parts of Puerto Rico and the U.S. Virgin Islands, the soils are less leached and thus contain more plant nutrients. However, in some cases, continued evaporation of soil moisture carries salts upward in the soils and tends to render them alkaline, hindering plant growth.
- Soils formed from weathered limestone on atolls and high limestone islands tend to have especially poor water- and nutrient-holding capacity.
- Steeply sloping high island soils tend to be shallow and easily eroded. [illegible] landslides.
- Alluvial soils created by deposition of silt from eroding upland soils are likely to have substantially greater fertility than those of the original site, but they will have the advantages of being mostly on flat land and closer to significant groundwater resources.
- Soils in natural or manmade low-lying wet areas filled with fine-grained sediment and decaying plant materials (e.g., swamps, taro pits) tend to be fertile but may become acid when drained and exposed to air.
- Maintaining an adequate supply of organic matter in highly leached soils is [illegible] way of partially alleviating the fertility problem.

crusts at or near the land surface in concentrations that few plants can tolerate (21). Similarly, if the groundwater table is high, evaporation of the groundwater may occur, which also results in accumulated salts in the soil. Thus, soils in drier zones tend to be alkaline such that even with irrigation systems and fertilizer applications, the availability of nutrients, and particularly of important trace elements can be a problem (28).

On high islands where slopes are steep, much of the rainfall runs off in streams rather than percolating into the ground. The soils that form on slopes remain shallow and can be more easily eroded than those on flatter lowlands (6).

The presence of soil organic matter from plant litter and roots plays a key role in maintaining soil productivity because it:

- contributes to the development of soil aggregates, which enhance root development and reduce the energy needed to work the soil;
- increases the air- and water-holding capacity (porosity) of the soil, which is necessary for plant growth and helps to reduce erosion;
- releases essential nutrients as it decays;
- holds nutrients in storage until the plants need them; and
- enhances the abundance and distribution of vital biota (45).

Soils formed from basaltic rocks in their early stages of chemical weathering can be quite fertile. Where annual precipitation is below 50 inches such soils can support high agricultural productivity; above 50 inches fertility decreases rapidly as leaching increasingly removes soil nutrients. As the weathering process continues, soil fertility will decrease even at the lower rainfall levels. Thus, geologically old, inactive volcanic islands generally will have soils with serious fertility problems and often aluminum toxicity as they become very acidic (pH 4.0). Those islands having geologically recent volcanic activity are more likely to have soils of higher fertility derived from basaltic lava flows and ash deposits. Where volcanic islands are still active or where they have been active recently it is less likely that sufficient time has elapsed for natural vegetation to develop to convert the rock materials into soil especially if precipitation is low.

Where rainfall is heavy the layer of weathered rock and soil material may become thick. Land-

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slides sometimes occur in such areas where heavy rains saturate this weathered zone and where the slope of the land is steep. Landslides of this sort are more common on high volcanic islands and continental islands than on raised limestone islands. Puerto Rico, for example, in 1981 and 1985 experienced severe landsliding on the south side of the island after saturating rains.

Soils formed from the weathering of limestone even where precipitation is moderate are composed of the residual insoluble minerals that have accumulated as the limestone dissolves (32). In this solution process the resulting soils are highly leached and, therefore, have fertility problems. Maintaining an adequate supply of organic matter in highly leached, infertile soils is a way of partly offsetting the infertility problem. Soils formed on coralline limestone atolls are composed of sand and silt-sized particles of limestone and, consequently, are alkaline (pH 7.5 to 8.5). The soils' lack of abundant amounts of clay-sized particles results in their poor water- and nutrient-holding ability. Decomposition of soil organic matter produces weak acids that in turn help dissolve the limestone soil particles (40).

Alluvial soils are those formed of eroded sediments that have been transported by running water. These sediments are deposited along floodplains and at the mouths of streams. The composition of the alluvium and, thus, the soil is a reflection of the eroded and weathered rocks of the watershed. For example, in a watershed comprised mostly of limestone, the alluvium on which the soil forms will be mostly limestone. Such soils are not likely to have greater fertility than the watershed soils, but they will have the advantages of being mostly on relatively flat land and closer to "significant" groundwater resources.

In low-lying wet areas, depressions sometimes are filled with a mixture of fine-grained sediment (clay, silt, and shell fragments) and decaying plant materials (peat). These dark colored, wet, soft deposits formed under anaerobic conditions generally are called "muck" soils. They are common beneath swamps and, thus, are restricted mostly to atolls and to lands of low relief surrounding some high volcanic islands, raised limestone islands and continental islands. The organic matter assists in holding added plant nutrients in a form available to living plant cover and provides other useful functions (see above). Because of their topographic position and nearness to the ocean, some have a high salt content. Others, when drained and exposed to air, become acid as certain sulfide minerals oxidize, adversely affecting plant growth.

Certain atolls, including some of those in the Marshall and Caroline Islands, are known for their rich deposits of rock phosphate. These deposits and soils have formed over time from dung or "guano" deposited on the atoll by fish-eating birds. Mild acids formed from the decomposition of organic matter carry the guano (phosphate bearing organic material) downward in the soil to limestone layers where the acids are neutralized and the calcium phosphate is deposited (40). Many of these phosphate deposits have been mined over the years and exported for agricultural use.

RENEWABLE RESOURCE SYSTEMS IN U.S.-AFFILIATED TROPICAL ISLANDS

The island ecosystems and the efforts to sustain, enhance, conserve, or restore these resources represent major positive factors of the U.S.-affiliated tropical islands. Each island ecosystem contributes to the supply and effective sustained use of island renewable resources (9). Island biological resources provide both direct and indirect benefits to the inhabitants. The small size of islands makes them easier to study as complete systems, and thus makes it possible to integrate management of island resources (9).

Local government efforts to maintain existing resources are numerous, including such actions as the creation of parks and protected areas, regulation of resource use, and development planning in coordination with sustainable use of local resources. The new entities emerging under the Compacts of Free Association now will have the opportunity to develop similar resource management programs. Previously, resource management and regulation, including protection of endangered species and critical areas, fell under the jurisdiction of the Trust Territory of the Pacific Islands regulations (47). However, regulatory efforts often were minimally effective and resources generally were well protected only on islands remote from human populations (14).

Common Characteristics of Tropical Island Resources

Endomism of Species

Tropical forests have a history of species-richness, and endemism. Puerto Rico has 547 native tree species, approximately the same number found in the continental United States. The U.S. Virgin Islands has between 800 and 1,000 native plant species and several hundred introduced or exotic species (44). The Western Pacific islands are especially rich in rare endemic species; for some tree species only one or two individuals are known[4] (44). In many

[4]For example, there are only a few individuals left of a native Pacific tree *Tabernaemontana rotensis* (M. Falanruw, pers. comm., 7/86).

Photo credit: J. Bauer

Habitat modification has reduced the range of the Puerto Rican parrot significantly. The only known remaining habitat for these birds, pictured here in an artificial nest, is in the Caribbean National Forest.

cases the insular bird and mammal life also are endemic. Examples include the Puerto Rican parrot and the Mariana fruit bat.

The number of species an island can accommodate is proportionate to island size (i.e., a greater number of species may live on a larger island); however, the number of species present on the island also depends on distance from colonizing sources (i.e., continents or other islands) and diversity of island habitat (9). Islands tend to develop new varieties and species that are found nowhere else (endemic species). This occurs as populations develop characteristics of adaptation to the isolated island environment. The small size of the island limits the species populations, thus, any reduction in habitat size, such as by human development, eventually may lead to extirpation or extinction of some species (table 3-2). Environmental perturbations easily may affect an entire population. The distance of islands from colonizing sources affects the probability that an extirpated population will naturally reestablish.

Value to Science

Island ecosystems provide values to science disproportionate to their small size. Because of the high rates of endemicity, islands may provide species of particular scientific interest for botanical and zoological investigation. The clearly defined boundaries facilitate study of species migration, competition, adaptation, and extinction. General principles of evolution can be derived from island studies (44).

The genetic resource represented by the unique island biota, although on a smaller scale than continental areas, represents potential gene banks of tropical species. Johnston Atoll is of particular scientific interest because of its geographic isolation and age (26). It is an ancient reef and, except for Wake Island, is the only atoll of the Marcus-Necker ridge still surviving in shallow water (app. B), The atoll has been designated a National Wildlife Refuge in order to protect the nesting seabird populations and well-developed coral reefs (26).

Vulnerability to Disruption

The isolation and small size of islands, which foster species endemicity and limit population size respectively, contribute to island species' vulnerability to disruption. Populations that evolved with limited competition or predator/prey relationships often cannot survive when forced to compete; further, small populations have lower capacities for recovery. Although isolation offers some protection from natural introduction of competing species, the importation (intentional or not) of animals, insects, and diseases has reduced island indigenous plant and animal populations (12,23). Guam's bird population has been declining steadily since World War II; the main culprit is thought to be the brown tree snake. The snake is believed responsible for severely reducing avian populations on Guam. The introduction of the snake has been estimated to have occurred in the early 1940s, however the method or reason for its arrival is not clear.

Table 3-2.—Endangered and Threatened Wildlife and Plant Species With Historic Range in the U.S.-Affiliated Tropical Islands

Common name	Scientific name	Historic range[a]	Status	Where endangered
Mammals:				
Little Mariana fruit bat	Pteropus tokudae	Western Pacific (Guam)	E	entire
Mariana fruit bat	Pteropus mariannus mariannus	Western Pacific (Guam) (Rota, Tinian, Saipan, Aguijan)	E	Guam
Dugong	Dugong dugon	East Africa to southern Japan, including RMI, CNMI, FSM, and Palau	E	entire
West Indian Manatee	Trichechus manatus	U. S. A., Caribbean Sea South America	E	entire
Caribbean Monk Seal	Monachus tropicalis	Caribbean Sea, Gulf of Mexico	E	entire
Hawaiian Monk Seal	Monachus schauinslandi	Hawaiian Archipelago	E	entire
Blue Whale ...	Balaenoptera musculus	Oceanic	E	entire
Bowhead Whale	Balaena mysticetus	Oceanic (north latitude)	E	entire
Finback Whale	Balaenoptera physalus	Oceanic	E	entire
Humpback Whale	Megaptera novaeangliae	Oceanic	E	entire
Right Whale, ...	Balaena glacialis	Oceanic	E	entire
Sei Whale . .	Balaenoptera borealis	Oceanic	E	entire
Sperm Whale . . . .,	Physeter catodon	Oceanic	E	entire
Birds:				
Guam Broadbill .,	Myiagra freycineti	Western Pacific Ocean (Guam)	E	entire
Mariana Crow	Corbus kubaryi	Western Pacific Ocean (Guam, Rota)	E	entire
Micronesia Kingfisher	Halcyon cinnamomina cinnamomina	Western Pacific Ocean (Guam)	E	entire
Mariana Mallard . . ,	Anas oustaleti	West Pacific Ocean (Guam, Mariana Islands)	E	entire
Micronesia Megapode (= La Perouse's)	Megapodius laperouse	West Pacific Ocean (Palau, Mariana Islands)	E	entire
Tinian Monarch	Monarcha takatsukasae	Western Pacific Ocean (Mariana Islands)	E	entire
Mariana Common Moorhen (= Gallinule) . . . .,..,.	Gallinula chloropis guami	Western Pacific Ocean (Mariana Islands)	E	entire
Puerto Rico Nightjar (=Whip-poor-will),	Caprimulgus noctitherus	Puerto Rico	E	entire
Puerto Rican Parrot	Amazona vittata	Puerto Rico	E	entire
Puerto Rican Plain Pigeon ., ...	Columba inornata wetmorei	Puerto Rico	E	entire
Piping Plover	Charadrius melodus	USA (Great Lakes, northern Great Plains, Atlantic and Gulf coasts, PR, Vi), Canada, Mexico, Bahamas, West Indies	E	Great Lakes watershed in IL, IN, Ml, MN, NY, OH, PA, and WI and Province of Ontario; All other range locations
Guam Rail	Rallus owstoni	Western Pacific Ocean (Guam)	E	entire
Ponape Mountain Starling.	Aplonis pelzelni	Western Pacific Ocean (Caroline Islands)	E	entire
Vanikoro Swiftlet, ., .,	Aerodramus vanikorensis bartschi	Western Pacific Ocean (Guam, Rota, Tinian, Saipan, Aguijan)	E	entire
Least Tern	Sterna antillarum	USA (Atlantic and Gulf coasts, Mississippi River Basin), Greater and Lesser Antilles, Bahamas and Mexico	E	range in contiguous States
Nightingale Reed Warbler	Acrocephalus luscinia	Western Pacific Ocean	E	Mariana Islands
Bridled White-eye	Zosterops conspicillata conspicillata	Western Pacific Ocean (Guam)	E	entire
Ponape Greater White-eye	Rukia longirostra	West Pacific Ocean (Caroline Islands)	E	entire
Reptiles:				
Culebra Island Giant Anole . .	Anolis roosevelti	Puerto Rico: Culebra Island	E	entire
Mona Boa ., ...	Epicrates monensis monensis	Puerto Rico	T	entire
Puerto Rico Boa, ... ,	Epicrates inornatus	Puerto Rico	E	entire
Virgin Islands Tree Boa	Epicrates monensis granti	U.S. and British VI	E	entire
American Crocodile	Crocodylus acutus	USA (FL), Mexico, South America, Central America, Caribbean	E	entire
Saltwater Crocodile	Crocodylus porosus	Southeast Asia, Australia, Papua New Guinea, Pacific Islands	E	entire
Monito Gecko ., ...,	Sphaerodactylus micropithecus	Puerto Rico	E	entire
Mona Ground Iguana . . .	Cyclura stejnegeri	Mona Island	T	entire
St. Croix Ground Lizard	Ameiva polops	U.S. Virgin Islands	E	entire

Table 3.2.—Endangered and Threatened Wildlife and Plant Species With Historic Range in the U.S.-Affiliated Tropical Islands—Continued

Common name	Scientific name	Historic range[a]	Status	Where endangered
Sea Turtles:				
Green	Chelonia mydas	circumglobal tropical & temperate seas and oceans	T	entire
Hawksbill	Eretmochelys imbricata	tropical seas	E	entire
Kemps Ridley (= Atlantic)	Lepidochelys kempii	tropical and temperate seas in Atlantic Basin	E	entire
Leatherback	Dermochelys coriacea	tropical, temperate & subpolar seas	E	entire
Loggerhead	Caretta caretta	circumglobal in tropical & temperate seas & oceans	T	entire
Olive Ridley (= Pacific)	Lepidochelys olivacea	tropical and temperate seas in Pacific Basin	T	entire
Golden Coqui	Eleutherodactylus jasperi	Puerto Rico	T	entire
Plants:				
Prickly-Ash	Zanthoxylum thomasianum	Northern Puerto Rico	E	entire
Beautiful Goetza, Matabuey	Goetzea elegans	Puerto Rico	E	entire
Vahl's Boxwood	Buxus vahli	Puerto Rico	E	entire
Palo de Ramon[b]	Banara vanderbiltii	Puerto Rico	E	entire
Hayun Lagu, Trokon guafi[c]	Serianthes nelsonii	Guam, CNMI	E	entire

Species Removed from the Endangered and Threatened Lists
(for informational purposes only, not codified in the Code of Federal Regulations)

Common name	Scientific name	Historic range	Prior status	Where endangered	Reason for delisting
Palau Dove	Gallicolumba canifrons	West Pacific Palau Islands	E	entire	recovered
Palau Fantail	Rhipidura lepida	West Pacific Palau Islands	E	entire	recovered
Palau Owl	Pyroglaux podargina	West Pacific Palau Islands	E	entire	recovered

[a]Historic Range indicates the known general distribution of the species or subspecies as reported in the current scientific literature. The present distribution may be greatly reduced from this historic range.

SOURCE: U.S. Department of the Interior, U.S. Fish and Wildlife Service, January 1966. [for all but the following]

[b]*Ecology USA,* "Recent Actions Under the Endangered Species Act, " 16(3):24, Jan. 16, 1987.
[c]Ecology USA, "Recent Actions Under the Endangered Species Act, " 16(4):32, Mar. 2, 1987.

A primary method of protecting island fauna is through the maintenance of appropriate habitat. However, the small size of islands means that park and protected area designs need to make optimum use of limited land area and may need to combine protection of fauna and flora. Undisturbed sanctuaries may be necessary for those species that cannot tolerate disturbance as opposed to those that maybe integrated into parks with recreational potential. Some extremely vulnerable species may only be effectively protected on islands remote from human population.

Surveys of many island areas still are needed to determine the incidence of endemism, and the status of native species. The importance of quarantine regulations and enforcement cannot be understated in island areas (23). Local governments can play a major role in identifying and protecting rare, threatened and endangered species. A native Guamanian plant species, Serianthes nelsonii, while pending Federal listing as "endangered" already possessed that status and protection under local law (42).[5]

Vulnerability to Overexploitation

Island species are particularly vulnerable to overexploitation, often because the base from which to build generally is small. Several island species have been exploited to the extent that they are now endangered (table 3-2). The Mariana fruit bat, *Pteropus mariannus mariannus,* is considered a great delicacy in the Marianas and bat populations on some islands have been heavily exploited. Overexploitation of fruit bat populations on Guam resulted in increased exploitation of fruit bat populations on other islands, including Yap, to satisfy the market. Consequently, Yapese fruit bat populations were severely reduced and in 1980 the hunting and exportation of these animals was

[5]S. *nelsonii* has been listed as Endangered under the Endangered Species Act, effective 3/20187.

Photo credit: E. Petteys

Overexploitation of the Mariana fruit bat has severely reduced populations in the Pacific. Despite protective legislation, poaching continues to threaten remaining fruit bat populations in some island areas.

banned. The species was placed on the Endangered and Threatened Wildlife and Plant list and given "endangered" status in 1984. Populations in some areas are in recovery stages (22).

Major Island Resource Systems

Upland Forests

The higher parts of most high islands in the U.S.-affiliated Pacific and Caribbean originally were covered by dense forests (9). The remaining higher elevation forests are important in contributing to control of erosion and landslides on steep slopes. The topography generally precludes timber harvesting operations but may allow some agroforestry practices.

Upland forests are important as wildlife habitat and in maintaining watershed function. These forests may enhance the watershed by increasing interception of rainfall, increasing percolation, improving infiltration, and reducing the rainfall impact on the soil. Upland forests are not easily reestablished once cleared, often leading to chronic erosion problems.

Mountainside submontane rain forests are comprised of predominantly broad-leaved trees with an even canopy, many epiphytes, and in some areas with abundant undergrowth including tree ferns and small palms. Forests of this type are found on several of the U.S.-affiliated islands. Some of the remaining submontane forests have been disturbed, such as one present on Truk, which now covers approximately only 2 acres on the top of one volcanic island.

Cloud forest (also called dwarf, elfin, or moss forest), a specialized, highly vulnerable upland forest, has developed on high ridges and mountain tops on some islands. These forests, kept moist by the constant presence of cloud formations, generally are composed of gnarled or dwarfed trees burdened with mosses and lichens. The ground commonly is covered with club mosses and ferns. Cloud forests are high in endemic species and are extremely vulnerable to disruption. Endangered status recently has been proposed for two plant species, *Cyathea dryopteroides* and hex cookii, endemic to Puerto Rico's cloud forests of the Central Cordillera (11). Although cloud forests are present on several of the islands, their areal extent is extremely limited.

Implications for Management.—Upland forests are important for watersheds, contribute to erosion control, provide habitat for wildlife, and often contain many endemic species. While development of forestland may be necessary for provision of goods and services to island populations, such activities might be preceded by objective analyses of the cost of artificially providing those services which will be lost because of development. Development

Table 3-3.—Ecosystems Present on the U.S.-Affiliated Islands

Island Areas	Puerto Rico	USVI	American Samoa	Guam	CNMI
Cloud forest	Present on mountain tops	May have been present on mountain tops	Undisturbed formation on top of Ta'u	Possibly on top of Mount Lamlam	Mount Tapachau, Saipan; other islands unknown
Submontane rain. forest	Formerly on higher mountains	None	Midelevation ridges and as secondary growth	None	None
Lowland rainforest	Little remains	None	Remains on steep slopes	Scattered remains of limestone, species-rich forest	Lava forest on northern island
Riverine and swamp forest	Limited extent remains	None	Limited amount present along streams	Present along rivers, moist ravines; mostly in south	In ravines on smaller islands
Subtropical moist/ seasonal forest	Little remains	Limited areas in mountains or remote areas	None	None	None
Subtropical dry forest	Present, little of original ecosystem	Present, considerably reduced from original extent	None	None	None
Savanna and grasslands	Considerable man-made areas maintained as pasture or ground cover	Present in former agricultural areas	Present as early sere after disturbance	Extensive fire-adapted areas in south	Extensive natural formation in northern islands, man-made on Saipan and others
Scrub	Present, often as secondary growth	Present	Present on on Matafao and Piao mountains, Tutuila	On rocky limestone coast and some southern areas	Coastal volcanic rock in north and limestone coast in south
Wetlands	Some rivers, and marshes, and some saltwater marshes occur behind mangroves	Saltwater ponds in bays behind mangroves	Streams and coastal marshes; lakes on Ta'u and Anu'u	Some streams and rivers; reed swamps; saltwater and freshwater marshes; man-made lake	Saltwater and freshwater marshes, freshwater lakes on Saipan and Pagan, brackish on Pagan
Mangrove forest	25 mi^2 scattered around coast	Forests only on St. Thomas and St. Croix	Pala lagoon (stressed) on Tutuila, and on Aunu'u	Small areas, particularly Apra Habor	Limited areas in southern islands
Atoll/beach forest and scrub	Present in some areas	Present	Widespread, special types on Rose Atoll and Swain's island	Common, includes some endemics	Present on some of the southern islands
Lagoons/shallow bottoms	Behind barrier reefs and other offshore features	Extensive in bays, inside reef and along shelf	Lagoons on Rose Atoll, Swain's Island and Tutuila	Cocos lagoon	Shallow lagoon inside some reefs on Saipan and Tinian
Coral reefs	Barrier, fringing and patch reef areas, most damaged	Bank barrier reef and algal ridge; also fringing barrier and patch reef complexes; some damaged	Main islands largely bordered by fringing reefs; some damaged	Barrier reef near Cocos island, variety of patch and fringing reefs elsewhere, some damaged	Fringing reefs common in southern islands, some damaged

SOURCE: A.L. Dahl, "Tropical Island Ecosystems and Protection Technologies To Sustain Renewable Resources in the U.S.-Affiliated Islands," OTA commissioned paper, Washington, DC, 1986.

could be redirected from areas where forest-provided services (i.e., important watersheds) are critical to the island and its inhabitants. Further, additional benefits maybe derived when required development is done in such a way as to protect or maintain the natural function of the-vegetation, thereby maintaining or only slightly reducing the services provided by the forest. The vulnerability of cloud forests to disturbance is so extreme that these forests cannot withstand development activities.

Lowland Forests

Lowland forests, which grow on hillsides and in coastal plains, are composed mostly of nu-

Table 3-3.—Ecosystems Present on the U.S.-Affiliated Islands—Continued

		Federated States of Micronesia			
Marshalls	**Palau**	**Kosrae**	**Pohnpei**	**Yap**	**Truk**
None	None	Present on mountain top	At highest elevations	None	None
None	None	At midelevations, some disturbed	At midelevations	None	Limited area on top of one volcanic mountain
None	Limestone, species-rich	Present with many endemics, nearly undisturbed	Present, most areas disturbed	Species-rich forests, most are disturbed or replaced	Present, disturbed
None	Along rivers and inland of mangroves	Along rivers and inland of mangroves	Dense along rivers, inland of mangroves	Present, inland of mangroves	Present, inland of mangroves
None	None	None	None	None	None
None	None	None	None	None	None
On smaller islets of some atolls	Present on clay soils, and where fire-maintained	Present	Present often from burning	Now predominant on clay soils, or where frequently burned	Present
Some on northern islands	Outer edges of limestone forest, rocky coasts and strip mined areas	Present	On rocky coasts and some ravines	Present in some degraded areas	Present
Freshwater pond on Lib; tidal saltwater marshes	Streams, rivers, lakes, ponds, swamps, freshwater and saltwater marshes	Short streams, and other freshwater habitat	Streams, rivers, lakes, ponds, swamps, and marshes	Freshwater streams, ponds, swamps, and marshes	Low swamps and marshes
In depressions on a few atolls	11,513 acres in estuaries and along coasts of archipelago	3,859 acres around island	13,562 acres along coast and estuaries, some on Pingelap Atoll	2,894 acres on Yap, and some on Elato and Woleai Atolls	3,315 acres around main islands
Largely replaced by coconut and breadfruit, except on some northern atolls	In a few areas behind beaches and on Kayangel Atoll	Present behind beaches	On high islands, largely replaced by planted trees	On atolls and behind beaches, often replaced by coconut	On atolls, islets; and in some coast areas
Large open lagoons, closed lagoon in Namorik	Lagoons within barrier reef, also Kayangel Atoll and Helen Reef	Some shallow lagoons inside reef	Extensive lagoon with seagrasses, and atoll lagoons	Some shallow lagoons within reef and atoll lagoons	Over 2,000 mi^2 including atoll lagoons
Islands built by coral reef ecosystems, some damaged	Barrier, fringing and patch reefs; rich and diverse; also some atolls; some areas damaged	Largely surrounded by fringing reef	Extensive barrier reef enclosing lagoon with fringing and patch reefs, and outer atoll islands	Wide, fringing reefs, outer atoll islands	Major barrier reef with islet enclosing lagoon with complex structures, outer atoll islands; considerable damage

merous species of fast-growing trees. Many of these reach 80 to 120 feet in height and exhibit a closed, uneven canopy and little undergrowth. Lowland rain forests occur on many of the U. S.-affiliated islands and most of these have been disturbed, some to great extent. The lowland forests of Kosrae and Palau probably represent the least disturbed communities.

Lowland rain forests are important for water catchment and for building soil nutrients and humus, often growing on and giving rise to the best island soils. They have the highest timber production potential of any island forest, however the land they cover often is under pressure for competing uses such as agriculture and human settlements. These activities, plus log-

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ging, have caused significant genetic resources and wildlife to be lost. Continuing disturbance, a lack of seed sources, and competition from introduced plants impede recovery, which might take decades under good conditions (9).

The drier Caribbean climate produces a type of lowland forest not found in the U.S. Pacific islands. The tree species of subtropical moist or seasonal forests are more resistant to drought and may lose some leaves in the dry season. Sixty percent of Puerto Rico originally was covered with this type of forest; this is down to 15 percent today (54). In the U.S. Virgin Islands, about 25 percent of the land area was covered with this type of forest. What remains today is mostly in mountainous regions with lesser amounts existing in the dry foothills (27). The conversion of land to agricultural purposes resulted in the clearing of the majority of this forest type.

Subtropical dry forest, a drought-resistant forest with many species and commonly with an understory of shrubs, also is found in the U.S. Caribbean. This type of forest is slower growing than the moist forest type. Sixteen percent of Puerto Rico was once covered by this vegetation type, mostly on the southern side and forest communities were distinguished between those growing on coastal areas and those of limestone soils (9). Five percent of the original forest type remains today primarily because of the conversion of land to agricultural purposes (54).

In the Virgin Islands this type of forest covered nearly three-quarters of the island (9). Today few original forest stands remain, most areas having been once cleared for grazing lands or other agricultural purposes. Forests of this type along the immediate coastal strip may be important in filtering runoff from the land and thus preventing or reducing coastal pollution from sedimentation and agricultural chemicals. Generally, relatively large areas are needed to maintain production and regeneration making the conservation of such forests difficult. Smaller areas, if effectively protected, may be managed to conserve this forest type (27).

Implications for Management.—These forests are important for water catchment, soil and humus building, and offer timber production potential. However, the relatively flat lands occupied by this forest type generally are under pressure for competing uses such as agriculture. Development and management activities might be directed to allow profitable use for timber and agroforestry production while maintaining the natural functions of the forest. Lands needed for other agricultural pursuits could be designated, so as to maintain sufficient amounts of natural and modified forest area. Abandoned agricultural areas could be reforested to restore soil fertility.

Freshwater Wetlands

Wetlands and freshwater island environments include freshwater marshes and reed swamps, lakes, rivers and streams with aquatic plants, and freshwater fauna. Dense forests of hydrophytic species also occur along rivers and in swampy areas inland of mangrove forests. Forests of this type occur in American Samoa, Guam, Northern Marianas, Pohnpei, Kosrae, Truk, Yap, Palau, and Puerto Rico. These forests are important in contributing to erosion and flood control along streambanks and thus prevention of pollution of water supplies.

Marsh and stream vegetation slows runoff, contributing to erosion and flood control and reducing water turbidity. They also may provide a filtration system which buffers reefs and lagoons from terrestrial sedimentation and pollution.

Wetland environments have been recognized as critical areas in island coastal management programs and as such are accorded some degree of protection (46,47,48,49,50,51). These environments also provide critical habitat for many wildlife species, including some that are federally protected under the Endangered Species Act,

These ecosystems may be very restricted on small islands and are generally quite vulnerable to disturbance. Some systems have evolved to adapt to a wide salinity range, or to temporary disappearance, regenerating when conditions permit. However, recovery from severe stress, such as from agricultural chemicals or heavy sedimentation, may be very slow even after sources of stress are removed (9).

Implications for Management.—Wetland environments provide critical habitat for many wildlife species and are important in contributing to erosion and flood control. Through mitigation of erosion and flooding they provide for the protection of nearshore areas from pollution and extreme freshwater discharge. Generally, wetland plant species are quite vulnerable to disruption and recovery may be slow; wildlife species may be extirpated if alternate wetland habitat is not available. Development activities could take precautions to protect the wetland environment, or be redirected to less vulnerable areas.

Grass and Fern Savanna Lands

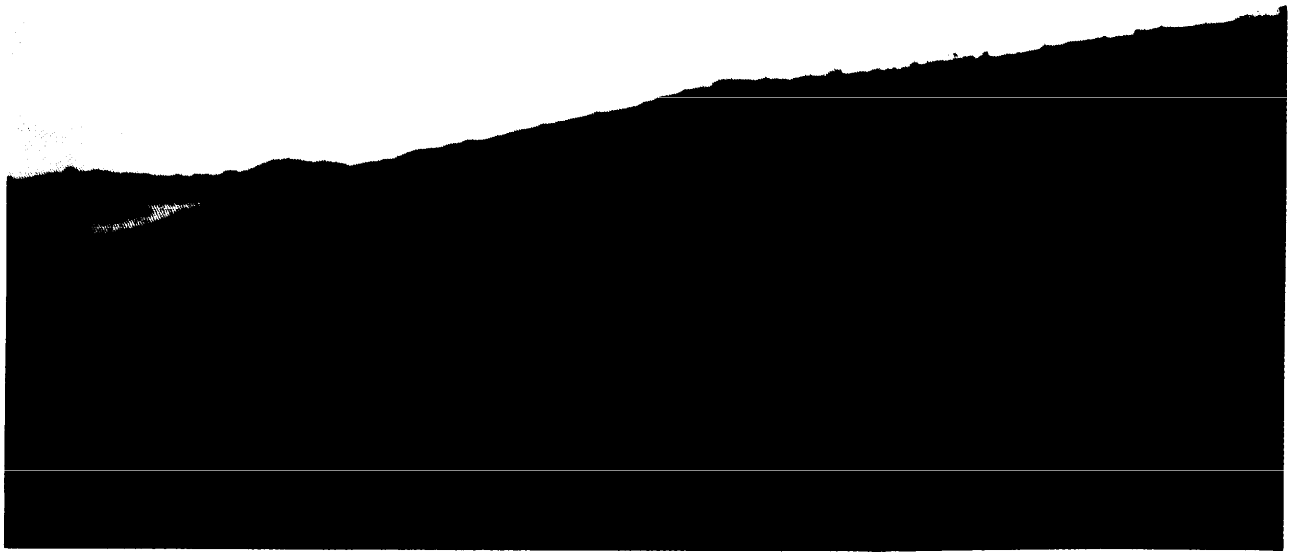
Savannas composed of grasses (commonly *Miscanthus,* or sword grass) or fern *(Gleichenia)* are found on many islands, alone or in association with scattered trees and shrubs. A number of endemic plants may be found in these areas. Many grasslands are maintained by frequent burning, often to attract game species, or provide pasture for domesticated animals. It is believed that the habitat has long been present in areas such as southern Guam and Babelthaup (Palau) although to a considerably lesser extent than at present (15).

Ferns and grasses tend to contribute to erosion control and some areas may be used as pasture land for livestock. However, improvement often is necessary to allow profitable use as pasture. Regrowth generally is rapid after burning, however, repeated burning degrades the soil by removing the organic content; and there is risk of fire spreading to adjacent more valuable forest types.

Implications for Management.—Primary management attention should be given to fire control and public education on the ecological impacts of frequent burning. Management or development activities could involve active improvement of those areas which might be used profitably for pasture, or agriculture, or for urban and residential development; and encourage reforestation of other areas. Such reforestation schemes could consider using fire tolerant species.

Strand and Beach

Vegetation comprised of a few widely distributed species of trees and shrubs, including some endemics, occupies the sand and rubble along the coastal beach strand close to sea level. This is the major vegetative formation on atolls and low coral islands. This coastal fringe contributes to stabilization of the coastline and offers protection from storm damage and salt-spray



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to inland areas. Strand forest and scrub can be found to some extent on all U.S.-affiliated islands. In many areas the forest has been cleared to allow for development. This type of forest has the capability to recover or recolonize readily when disturbance or stress is removed (9).

In some areas much of the strand and beach vegetation has been removed and replaced with more economically profitable plant species. On many of the Marshall Islands, for example, areas formerly occupied by beach and strand vegetation now are planted largely with coconut palms and breadfruit trees.

Implications for Management.—Strand and beach vegetation contribute to retardation of coastal erosion as well as protection of inland areas from salt-spray and storm damage. Development activities could strive to maintain some extent of this vegetation zone for its protective function, particularly on more vulnerable atolls and low coral islands. Enrichment of existing stands with more desirable or profitable species may offer an opportunity to preserve some protective functions as well as provide a food or income source.

Mangrove Forests

Mangrove forests are characterized by salt-resistant trees, some with stilt roots or pneumatophores, growing in the intertidal range along ocean shores or estuaries. Nutrients from terrestrial runoff and the leaves falling from the trees provide food and shelter for marine life living among the roots. A significant amount of mangrove forest area remains in the U. S.-affiliated Caribbean islands; nearly 25 square miles of mangrove forest is scattered around Puerto Rico's coastline. While scattered mangrove trees occur along the coast of the U.S. Virgin Islands, mangrove forests only survive

Photo *credit: C. Wahle*

Mangrove forests, found to some extent on most of the U.S.-affiliated islands, provide important habitat and nursery areas for many marine and terrestrial species. The extent of these forests has been significantly reduced through human development activities.

at Salt River, St. Croix and Jersey Bay, St. Thomas; the larger mangrove areas have been cleared for development (9).

In the U.S.-affiliated Pacific islands, Pohnpei and Palau have the largest extent of mangrove forests (13,652 and 11,513 acres respectively), followed by Kosrae (3,859 acres), Truk (3,315 acres), and Yap (2,894 acres) (9,56). American Samoa has limited mangrove forest areas (130 acres) (56), one of which (Pala Lagoon) is under stress from nearby development. In the Northern Mariana Islands there are only small mangrove areas and they may be threatened by dredging and development.

Mangrove forests are important in the maintenance of the nearshore coastal water quality. They are important for many marine species that are dependent on the protected habitat for food and shelter (8). They also trap and stabilize sediment from runoff, thus building land and protecting the coral reefs and lagoons from pollution. Mangroves may regenerate after short-term physical disturbances such as storms, however longer term disturbances such as changes in runoff can destroy a forest. Reestablishment of mangroves has been practiced in Florida and Puerto Rico indicating that, if conditions are appropriate, the forest can regenerate in a period of 10 to 15 years. An oil-damaged mangrove stand in Guam has been successfully rehabilitated through a replanting program. The program involved removing the damaged trees and replanting seedlings that were harvested from an undisturbed area of the forest. However, regeneration of clear-felled areas in Southeast Asia has not been successful (9).

Implications for Management.—Mangrove formations are important for a variety of functions including, filtration of freshwater, wildlife habitat, nutrient provision for nearshore marine life, erosion control, and limited timber production. Development activities which would remove mangroves should be redirected to other areas, and timber harvesting should be limited to sustainable yields.

Seagrass Meadows

Seagrass meadows commonly are found in association with coral reefs and provide shelter and nursery areas for many marine species. Lagoon bottoms and other shallow coastal waters support seagrass and algal beds. The sand and mud bottoms create habitat for many burrowing and benthic organisms (9).

Algal and seagrass meadows are highly productive ecosystems that serve as "pastures" for many commercially important marine species (9) and appear to foster an increased variety of reef fishes (20). They also act to stabilize bottom sediments and thus help prevent coastal erosion. To some extent they may absorb organic wastes, however heavy sedimentation can cut off light and smother the bottom (9).

Implications for Management.—Seagrass meadows contribute to the retardation of coastal erosion, provide habitat and feeding grounds, and may absorb some organic wastes. Destruction of seagrass meadows generally is a repercussive impact from other actions. For example, increased sedimentation from development activities may smother bottom communities and boat anchors may remove large patches of seagrass. Recovery is slow from such disturbances. Seagrass meadows could be protected through appropriate actions incorporated in development activities, such as efforts to reduce erosion, or establishment of permanent moorings in frequently used areas.

Coral Reefs

Although tropical waters commonly have low nutrient levels, coral reef areas are sites of high biological productivity. Coral reef areas, associated with most of the U.S.-affiliated tropical islands, are among the most productive of tropical marine areas (55) and represent a highly valuable resource.

The reef areas provide shelter and habitat as well as a nursery for many marine organisms. Hundreds of edible varieties of fish including jacks and some species of snapper, commonly are members of the reef community, as are many mollusks and crustaceans (17,41,52). Harvesting of nearshore marine resources takes place primarily in the vicinity of coral reefs and seagrass beds (20) and thus much of the nearshore fishery potential corresponds to the interrelation of the coral reef, seagrass meadow, and mangrove forest ecosystems.

The nearshore waters of many of the U. S.-affiliated Pacific islands support important subsistence fisheries. A recent survey indicated that at least 40 percent of American Samoa's households exploit the nearshore fisheries for a part of their food (46). This level is estimated to be as high as 90 percent in the Caroline and Marshall islands (17).

The physical structure of the coral reef provides a natural breakwater which retards shoreline erosion (20) and provides for the replenishment of beach sand; as wave action scours the reef structure, particles break off and are carried to shore. Coral reefs also represent a major tourist attraction and valuable recreational resource for activities such as diving and snorkeling.

Destructive fishing practices (e.g., dynamiting, bleaching), coastal development activities that increase freshwater discharge or turbidity of nearshore waters, or expulsion of thermal or chemical effluent all may cause reef destruction. Pest outbreaks such as the crown-of-thorns starfish *(Acanthaster plancii)* similarly damage coral reefs. While the values of coral reefs are well understood, enforcement of protective regulations still poses a problem in some areas.

Implications for Management.—The diverse benefits provided by coral reefs, including enhancement of fishery potential, marine species habitat, protection from shoreline erosion, beach sand replenishment, and recreational value, clearly demonstrate the importance of this nearshore marine structure. Activities which are known to have adverse impacts on coral reefs should be discontinued through an effective regulation and enforcement program. Coral reef management should consider sustainable multiple use of the resource: allowing recreation (snorkeling, fishing), fishery, and tourist use of reef areas while affording necessary protection.

EFFORTS TO SUSTAIN RESOURCES ON U.S.-AFFILIATED ISLANDS

The favorable climate of the U.S.-affiliated islands of the Pacific and Caribbean contributes to conditions capable of sustaining relatively high rates of aquatic and agricultural productivity. Although some island areas experience an annually occurring dry period, the warm temperatures and generally substantial rainfall common to the islands allow a continuous growing season. Puerto Rico has features that allow cultivation of subtropical crops. The climate and esthetic characteristics of tropical islands also make them prime tourist attractions, and in some cases tourism and related enterprises comprise a large part of the island economy.

Tropical island ecosystems offer a wide variety of products and services to island inhabitants. The importance of these ecosystems to the quality of life has long been understood by the islanders and traditional practices were inextricably linked to the workings of nature. As modernization increased and less conservative practices were adopted, some of the unique island environment was transformed or damaged, Nevertheless, some undisturbed areas remain today.

Efforts to maintain and enhance existing resources have resulted as concerns have increased over adverse trends in resource use, degradation, and associated productivity loss. In some cases, these concerns have prompted the development of resource sustaining management plans which provide for the creation of parks and protected areas, regulation of resource use, consideration of development's impacts on the environment, and investigation of alternatives to heavily exploited resources (see app. E).

Efforts To Maintain the Resource Base

Traditional subsistence economies embodied conservation of critical renewable resources. As economies shift from subsistence to cash and populations increase, the impacts of rapid growth on renewable resources becomes evident. Attention is now being given to mechanisms to protect and maintain critical renewable biological resources. Resource areas and wild populations which suffered past degradation have been examined in order to develop methods to maintain their viability. In some areas, resources, although perhaps modified by human activities, remain in good condition.

Regulatory or conservation actions instituted at both the local and Federal level have acted to preserve areas of critical importance. The Caribbean National Forest, federally established in Puerto Rico's Luquillo Mountains in 1903, originally consisted of 18,000 acres and, was the first tropical National Forest (10). Subsequently, additional tracts of land were protected under the Commonwealth forest system. Today there are 14 protected forests on Puerto Rico comprising nearly 100,000 acres of protected forestland.

The United Nations Man and the Biosphere Program (UNESCO-MAB), established in 1971, works to promote international scientific cooperation and the study of human interaction with the environment. Biosphere reserves are part of a worldwide network of protected land and coastal environments and enfold many functions including conservation, research and monitoring activities, education and training, and cooperative efforts with various scientific organizations. The design of the biosphere reserve attempts to integrate conservation with surrounding socioeconomic needs. There are three designated biosphere reserves within the U.S.-affiliated Caribbean islands: Luquillo Forest (28,112 acres) part of the Caribbean National Forest on Puerto Rico; Virgin Islands National Park (15,188 acres) on St. Johns Island in the U.S. Virgin Islands; and Guanica Commonwealth Forest Reserve on Puerto Rico (9,930 acres). The only designated biosphere reserve in the U.S. Pacific islands is located on Hawaii (43,53).

Local and National Wildlife Refuges have been established on many of the U.S.-affiliated islands. In some cases entire islands are designated as refuges, such as Howland, Baker, Jarvis, and Rose atolls in the Pacific. Habitat loss has been implicated as a major cause for loss of wildlife species (51), thus, through the establishment of wildlife refuges native fauna and flora may be afforded protection.

Similarly, the harvesting of corals and other sessile marine animals is restricted in the waters of u. S.-affiliated islands in the Caribbean by various Federal and Commonwealth statutes. Conchs and four species of sea turtles (hawksbill, green, leatherback, and loggerhead) are protected from harvesting because of their endangered species status (55).

The Coastal Management Plans created by many of the U.S.-affiliated islands contain provisions for establishment of Areas of Particular Concern–areas recognized to fulfill valuable functions (ecological, social, esthetic) in the island ecosystems. These areas are being protected on some islands, and uses to which they are best suited are being encouraged. For example, the Commonwealth of the Northern Mariana Islands Coastal Management Program contains plans to assure adequate water flow, nutrient levels, and oxygen levels for mangrove/wetland environments. These environments are recognized to be important in natural drainage patterns and as wildlife habitat (47).

In addition, progress has been made in the last few years in the preparation of resource inventories in some of the U.S.-affiliated islands. Some are already complete and others are underway (9). However, a need for biological inventories still exists on many of the islands. Such information can assist in creating protected park areas that in turn can help reduce resource overharvesting (55).

Efforts To Restore the Renewable Resource Base

Despite the fact that population needs exceed the supply of renewable resources on most islands, interest in conservation exists. Many basic marine conservation measures developed in the West in the past century were traditionally practiced in the Pacific islands. Examples include establishing closed seasons and restricting the kinds of fishing gear allowed (15,25),

Federal and local efforts to increase forest area in Puerto Rico have been quite successful. Since 1981, the Puerto Rican Forest Service, with technical assistance from the U.S. Forest Service, has taken an active role in promotion of resource conservation and forestry development (10).

Other cooperative efforts involve species recovery programs. For example, efforts focused largely on the bird population of Guam are being carried out in conjunction with the U.S. Fish and Wildlife Service (23). Similar efforts to recover the Puerto Rican parrot have been ongoing since 1968 (54).

Efforts To Redirect Use Of Underused Resources

Although many renewable resources have suffered degradation from overexploitation, some seem to be underused: exploited at rates below their maximum sustainable yield. Some local governments are working to identify these resources and redirect resource use. For example, current fisheries development policy in Puerto Rico emphasizes underused resources, such as swordfish, which may help divert fishing effort from overexploited nearshore stocks (20).

Many nonfood resources of the U.S.-affiliated Pacific islands, such as pearl oysters, have been underexploited since World War II because little effort has been made to develop their potential. The success of the Japanese pearl culture prior to World War II suggests that such an operation is viable, given proper planning and management. Although the status of the species introduced by the Japanese is not known, several species of pearl oysters occur naturally in Palau, Yap, Truk, and Pohnpei, and black-lipped pearl oysters have been found in high densities near some atolls in Pohnpei State.

Further opportunities exist to develop underused land, plant, and animal resources. For example, a survey of Guam's agricultural land resources indicated that no more than 2 percent of the land is actively cultivated (23); this percentage may change seasonally and in relation to market and climate conditions (33). In Puerto Rico, abandonment of coffee plantations and farmlands, particularly on steep slopes, released 1.1 million acres which are now potentially available for forestry and agroforestry activities and recreation (44).

Efforts To Culture Species

Another avenue to reduce stress on natural populations and environments is to develop culture systems for those species currently harvested on a fishing, hunting, or gathering basis. The success of culture systems may depend on more than just the biological factors of the desired species. Considerations include the availability of primary research, development of appropriate techniques, technical assistance, and sociocultural and economic factors.

The level of interest in aquiculture of numerous species that already are a part of islanders' diets is high in all of the islands. Most island groups have done preliminary work to determine the feasibility of culturing a number of marine and freshwater species of fish and shellfish (31). Developing culture techniques for such organisms can transform them from roles of only subsistence importance to those of economic importance. Of course, if markets expand faster than culture activities, increased pressure may be put on natural populations due to their increased value. Despite the growing interest in and knowledge about aquiculture of warmwater species, numerous projects have been unsuccessful.

A number of products currently are gathered from indigenous and naturalized plants. Development of culture systems for some of these plants might allow increased yields such that they could develop economic as well as nutritional significance. For example, a wild variety of cinnamon *(Cinnammnum carolinensis)* grows on Pohnpei and is used as medicine and a tea-like beverage. Similarly, perfume oils can be extracted from certain plants now growing wild on Pacific islands (e. g., ambretta oil from *Hibiscus abelmoschus;* ylang-ylang oil from *Cananga odorata).* Ylang-ylang petals currently are used for traditional ornamental headwear (mwarmwars). Research and small-scale production at the Ponape Agriculture and Trade School indicates that ylang-ylang can be cultured profitably and processed to supply fragrance oils for locally produced coconut soap and for export.

Finally, native and naturalized plants have, over time, adapted to a range of environmental conditions (2). They represent a reservoir of genetic resources that could be used in plant selection programs, and might allow expansion of agriculture to infertile, saline, and degraded lands. Biological inventories that characterize plant species composition (e.g., nutritional, medicinal values) and land race characteristics are needed in many areas to promote this effort *(27).*

Enhancement of Existing Renewable Resources

Programs to enhance existing resources have developed concurrently with interest in alternatives to heavily exploited resources. For example, in 1984, one-third of Puerto Rico was covered by forest, mostly in second-growth forests, fruit tree plantations, and shade trees for coffee. These forests supply little useful timber, although they provide excellent watershed protection, wildlife habitat, and recreational and esthetic opportunities. Enrichment of forests through underplanting of valuable species offers one method of increasing forest value. Many larger Pacific islands could sustain timber production to help meet local needs through similar efforts (44).

In most island areas, efforts have been made and continuing studies are underway aimed at enhancing the productivity of reef flats through the introduction of artificial habitats. Studies indicate that artificial reef habitat enhancement can increase local fish abundance and potential harvests (3). Similarly, artificial upwellings, which draw nutrient rich water to the surface, may enhance fishery potential. Enhancement programs, as well as research to determine impacts of reorganization of ecological structure, will be necessary in order to allow the sustainable production of some species (e.g., trochus) while maintaining the balance of the associated natural systems (39).

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