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FINAL REPORT

CLASSIFICATION OF COASTAL AND MARINE ENVIRONMENTS FOR IDENTIFICATION OF BIOSPHERE RESERVES

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CONTENTS

I. GOAL

The Action Plan for Biosphere Reserves (UNESCO, 1984) was adopted as a result of the First International Biosphere Reserve Congress. The plan includes "Recommended Actions" of which Action I is:

> "In order to provide the basis for a rational selection of biosphere reserves that would give a complete biogeographical cover, IUCN, in cooperation with UNEP, should prepare and publish:
>
> *classification of 'representative ecological areas' on the land; and
>
> ***classification of 'representative ecological areas' covering intertidal and marine habitats in coastal areas."**

The goal of this proposal is to develop a method to classify coastal and marine environments of the world, with an initial focus on the Caribbean Region, for purposes of identifying potential biosphere reserves.

II. OBJECTIVES

In order to meet the goal, it is necessary to:

1. evolve a conceptual framework for identifying functional coastal units, emphasizing ecological processes;
2. develop a thematic, map-based information system to describe and illustrate the dominant processes, species, and habitats characteristic of the region;
3. conduct selected case studies of representative sites;
4. provide guidelines for identification and selection of Biosphere Reserve sites for the region as a whole;

5. provide training opportunities at all stages of work.

Classification is necessary for the identification of potential biosphere reserves. The initial objective is to identify a minimum unit for analysis. This can be represented by a model which recognizes the importance not only of the geographic limits of ecosystems, but also the significant flows of energy and materials through them. Within each region, a manageable number of unit types is recognizable, each type incorporating a cluster of characteristic habitats and species. Indicator species serve as useful tags to habitats and also to controlling ecological processes.

This project also seeks to identify units appropriate for regional research. The International Coordinating Council of the Programme on Man and the Biosphere (MAB), at its October 1986 meeting in Paris, adopted four research areas (UNESCO, 1986):

- Ecosystem functioning under different intensities of human impact;
- Management and restoration of human-impacted resources;
- Human investment and resource use; and
- Human response to environmental stress.

These research areas reflect the perspective of human beings within an ecosystem context. However, this context is not yet apparent for coastal and marine systems. Thus, in addition to providing a framework for biosphere reserves, an overall objective is to identify coastal/marine ecosystems, at least operationally.

In order to attain our objectives, it is necessary to conduct a comparative study in a region of intrinsic interest, which will; a) demonstrate the value of the approach to conservationists and managers; and b) be of immediate practical value.

III. BACKGROUND AND CONCEPT

A. CLASSIFICATION HISTORY.

A "classification" is a systematic arrangement of entities or concepts based on the similarities and differences among the elements to be classified. It results in a hierarchical taxonomy and provides insight into ecological relationships. It is hierarchical, as evidenced by such terms as "biome," "realm," "region," and "province", which are applied to descending orders of geographic scale. Several hierarchical biogeographic classifications exist (e.g., Küchler, 1964; Udvardy, 1975; Bailey and Cushwa, 1982) that attest to their heuristic value. However, no appropriate classification exists that would aid in the selecton of "representative" areas for biosphere reserve designation (UNESCO, 1984) for coastal or marine systems.

Environmental classifications have not usually been based on functional ecological units. Rather, they have mostly been based on biotic assemblages. By definition, design, and practice they emphasize the uniqueness of regions. Consequently, they are of limited use in identifying the comparative ecological roles which are played by different species in different regions. Such biogeographical assemblages cannot readily be used to identify "representative ecological areas," as called for by UNESCO (1984), nor are they easily applied to predictions about consequences of perturbation.

Traditionally, classification schemes have been separately developed for terrestrial, coastal, or marine environments. For example, Udvardy (1975) has classified terrestrial areas largely on the basis of zoogeography and vegetation types. Dolan et al. (1972) used physical landforms and physical processes to classify coasts. Other investigators of coastal and marine systems have used physical characteristics, such as temperature and salinity, to define water masses (Dietrich, 1963), or biological characteristics such as the presence of indicator species, to define oceanic provinces (Meek, 1928; Stephenson and Stephenson, 1950; Voss and Voss, 1955; Colebrook and Robinson, 1963; McGowan and Walker, 1985; Springer, 1982).

Attempting to extrapolate from such environment-specific schemes to other physiographic environments creates problems. Some of these problems, such as using vegetation (broadly interpreted to mean plant or photosynthetic matter) to classify marine environments, are obvious. Others, such as the inherent difference in the dimensionality of the terrestrial (2-dimensional) versus the marine environment (3-dimensional), are not quite so obvious. In fact, as Hayden, Ray, and Dolan (1984) have stated, it is a scientific challenge to develop an "internally consistent world system of classification" that can be adapted to the many physio-biogeographic environments on this earth without compromising the underlying concepts of the scheme.

B. "COASTAL ZONE" DEFINITION

Ketchum (1972) recognized the coastal zone as "a natural entity with flexible boundaries" and defined its boundaries as "the extent to which man's land-based activities have a measurable influence on the chemistry of water or on the ecology of marine life." This means that entire watersheds and waters covering the extent of the continental shelf, and even beyond, are included. This defines the coastal zone as a major subdivision of our planet. Hayden, Ray, and Dolan (1984) adapted this definition, as follows: "(1) the terrestrial boundary is defined by (a) the inland extent of astronomical tidal influence, or (b) the inland limit of penetration of marine aerosols within the atmospheric boundary layer and including both salts and suspended liquids, whichever is greater," and "(2) the seaward limit is defined by (a) the outer extent of the continental shelf (approximately 200 m depth), or (b) the limit of territorial waters, whichever is greater."

Inman and Nordstrom (1971) have provided perhaps the most basic approach to the coastal zone -- that of plate tectonics. They state that coasts "represent complex associations of tectonic development modified by the combined actions of many different agents and processes -- including marine, terrestrial, and organic -- all subject to the effects of the large variations in sea level during the late Pleistocene." It is important to emphasize that tectonic processes have been occurring for the Earth's entire history; the biota have had to adapt to these processes for millenia and, therefore, one would expect a direct relationship between geomorphologic and biotic patterns on global to local scales.

From this latter perspective, the challenge is to differentiate the coastal zone within a global context, that is, to recognize an area that covers about 8% of the Earth's surface, or about 1.5 times the size of Africa. The global continental shelves alone cover 29 million square kilometers, ranging in width from 0-1300 km, averaging 74 km (Inman and Nordstrom, 1971). The volume of just the watery portion of the coastal zone is about 3 million cubic kilometers or about the total volume of all terrestrial life. Over 90% of known marine species occur in coastal zone waters. The coastal zones, both land and sea portions, are about as productive as tropical forests (portions of tropical forests fall within the coastal zone, according to our definition). Most striking is that over 50% of the human population lives within this zone, deriving a large proportion of resources there, including over 90% of commercial fisheries.

Geopolitical aspects of the coastal zone loom equally important as geomorphological and biological ones. One hundred thirty-nine nations, world-wide, have coastlines and 113 of these have declared Exclusive Economic Zones in concordance with the Law of the Sea. Thus, over 90% of currently exploitable living and non-living marine resources have recently come under national jurisdiction. Yet, most of these nations have little marine science capability, nor do most international aid agencies possess such capacity.

Lack of appreciation of the extent and nature of the coastal zone results in a startling world-wide vulnerability of coastal-marine resources, and of our ability to conserve or to use them in a sustainable way. The compound influences of industrial development and urbanization within the coastal zone produce heavy stresses on coastal habitats, species, and productivity (CEQ, 1979; UNEP, 1982, NOAA, 1984).

C. AN ECOLOGICAL, PROCESS-ORIENTED CLASSIFICATION

It has recently been proposed by members of this research team and others (Odum et al., 1974; Ray et al., 1981; Hayden, Ray, and Dolan, 1984; Ray, 1985) that a process-oriented classification scheme based on physical and biological structure and interactions can be applied consistently to most, if not all, geographic/ecological provinces. The floral, fauna, and ecological characteristics of any one geographic location can be distinguished from others by means of different sets of interactions. As an example, high-energy coastal areas can be separated from low-energy ones on physical grounds. Also, areas with differing biological components, but which exhibit similar interactions among the species present, would also be represented as different by the classification process.

Hayden, Ray, and Dolan (1984) used physical processes to determine the extents of realms, regions, marginal seas, marginal archipelagos, and coastal boundaries at a global macroscale (figure 1 and tables 1 and 2). Coastal biotic provinces matched well with physical coastal boundaries. Physical processes seem to dominate the distributions of the biota of coastal systems (cf. Mann, 1982). The same may also be true of pelagic and oceanic-benthic systems (e.g. McGowen and Walker, 1985); however, biotic provinces for these have not yet been determined, world-wide, consistent with methods that have traditionally been used to define coastal provinces, e.g., by species endemism, (Briggs, 1974).

The concept we present here is at a smaller scale of spatial resolution than our earlier work. Our goal is to define recognizable ecological units on subregional-to-local scales, in which internal interactions are identified, consistent with the concept of ecosystems as functional units. The units so defined imply that homeostatic interactions exist that impart a measure of predictability to these ecosystems. If such within-unit processes can be identified, it also appears obvious that these can be incorporated as guidelines into conservation and management practices.

1. <u>Definition of Units for Classification</u>

At the time of our earlier work, we noted that the next level of research required the consideration of mass, energy, and living resources that are exchanged across the coastal zone, especially those exchanges that are associated with

FIGURE 1

CLASSIFICATION OF THE ATLANTIC OCEAN REGION

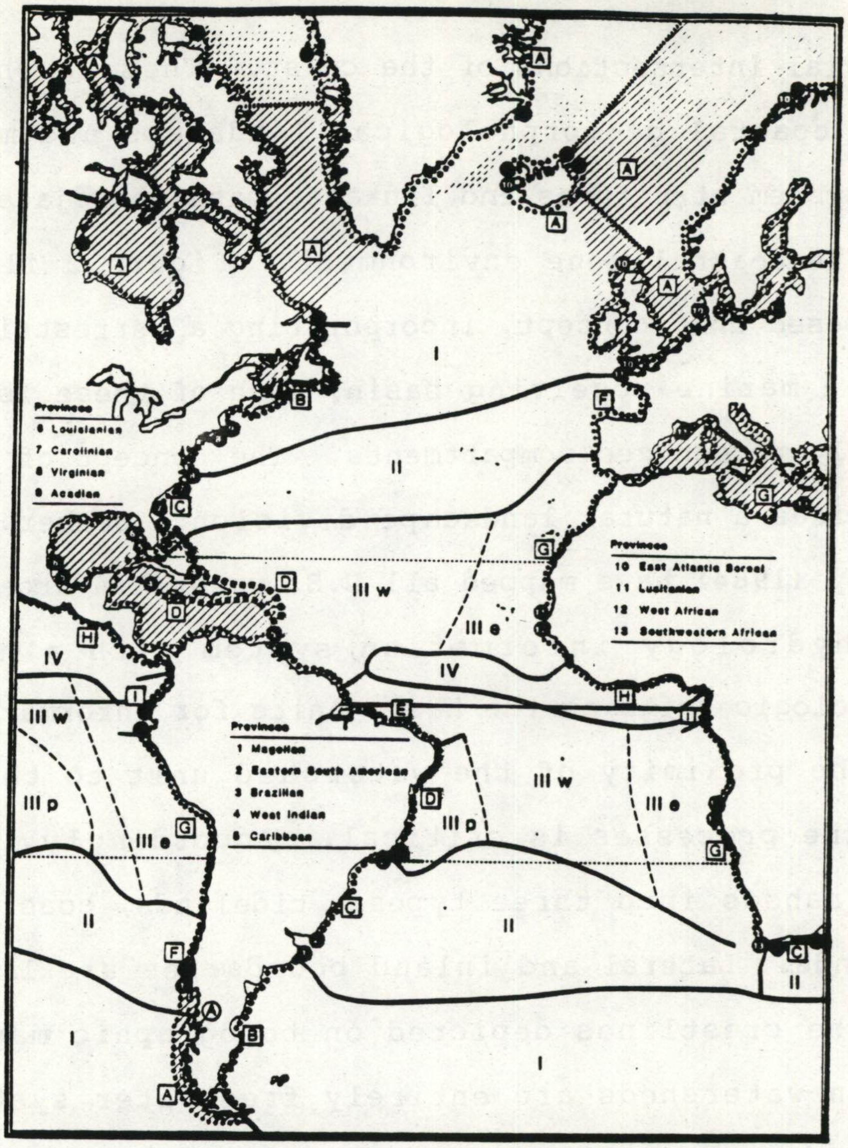


TABLE 1

Ocean Realms.

Oceanic Realm	*Direction of Surface Currents*
I	Variable eastward currents
II	Weak and variable currents
III	Trade-wind currents
III[e]	Strong equatorward currents
III[w]	Westward currents
III[p]	Strong poleward currents
IV	Strong westward and equatorward currents
V	Monsoon currents (seasonal reversals)

TABLE 2

Currents and Windstreams of Coastal-margin Realms.

	Dominant Directions	
Coastal Realm	*Currents*	*Windstreams*
Arctic (M)	ICE	W
Antarctic (L)	W-ICE	W
Subpolar (A)	W	W
Eastern		
Temperate (B)	P	E
Monsoon (J)	EQ/P	ON/OFF
Subtropical (C)	P	P
Tropical (D)	W	W
Intertropical (E)	W*	W*
Western		
Temperate (F)	P	P/EQ
Monsoon (K)	P/EQ	ON/OFF
Subtropical (G)	EQ	EQ
Tropical (H)	EQ	W/EQ
Intertropical (I)	E/EQ	EQ

SYMBOLS: ICE = Ice-margin coast; P = Poleward; EQ = Equatorward; W = Westward; E = Eastward; ON = Onshore monsoon; OFF = Offshore monsoon; / = Winter–Summer seasonality; * = seasonality in hemisphere source-regions of currents and windstreams. *The symbols used on the maps are given in parentheses above.*

fluvial intersections of the coast. These exchanges sculpt the coastal geomorphological landscape and make possible ecosystem structures and linkages between adjacent ecosystems of the coastal zone environment. Figure 2 illustrates our proposed unit concept, incorporating a terrestrial watershed and a marine receiving basin; each of these is divided into easily recognized compartments. The concept of the watershed provides a natural landscape division. Seaber, Kapinos, and Knapp (1984) have mapped all U.S. watershed areas to provide an hydrology information system with a hierarchy of hydrologic units as the basic units for information storage.

The proximity of the watershed unit to the sea and to marine processes is critical. Accordingly, we classify watersheds into three types: tidelands, coastal plain, and uplands. Lateral and inland boundaries are largely defined by the crestlines depicted on topographic maps. Coastal plain watersheds are entirely freshwater systems that are restricted to the seaward-sloping surface of clastic materials that usually has been a sea bottom and that is now above sea level. Their inland limits are fall lines or transitions to complex topographic relief. Upland watersheds are inland of the coastal plain. They may be immediately inland from the coast where more complex terrain forms the coastal interface, or hundreds of kilometers inland in other areas. They must be considered as functional parts of our classification because of their freshwater discharges, which deliver energy, particulates, and important chemical

FIGURE 2

COASTAL UNIT CONCEPT

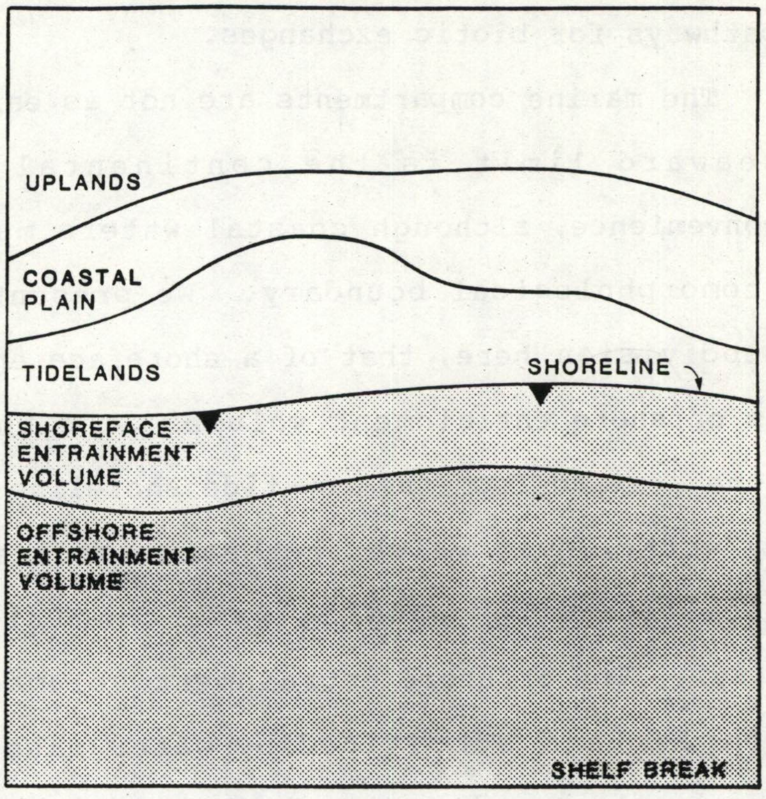


TABLE 3

LONGSHORE BOUNDARIES

(EXAMPLES)

- HEADLANDS, CAPES, AND SHOALS
- CHANGES IN SHORE ORIENTATION
- CIRCULATION DISCONTINUITIES
- SUBMARINE TOPOGRAPHY AND CANYONS

TABLE 4

CONTROLS

- WATERSHED AND RECEIVING BASIN MORPHOLOGY
- TERRESTRIAL AND MARINE CLIMATES
- WINDS, WAVES, CURRENTS, AND TIDES
- FLUVIAL DISCHARGE, BEDLOAD, SUSPENDED LOAD, AND DISSOLVED LOAD
- TERRESTRIAL AND MARINE BIOTA
- HUMAN LAND/SEA USE

nutrients to coastal and marine waters. They also provide pathways for biotic exchanges.

The marine compartments are not as easily delimited. The seaward limit is the continental shelf break as a convenience, although coastal waters may extend beyond that geomorphological boundary. We present only the simplest subdivision here, that of a shoreface entrainment volume and an offshore entrainment volume. The shoreface is a "narrow zone seaward from the low tide shoreline permanently covered by water, over which the beach sands and gravels actively oscillate with changing wave conditions" (Baker et al., 1966). The offshore entrainment volume can be exceedingly complex and subdivided by water masses, oceanic fronts, gyres, the morphology of the coast (e.g., the presence of lagoons, etc.), shelf width, and benthic topography (e.g., canyons, etc.). However, we have not subdivided this entrainment volume here for reasons of simplification and to ensure that the resulting classification can be applied worldwide.

The longshore boundaries of the marine portion of coastal units may be determined by factors listed in table 3. Some of these boundaries are relatively easily defined, e.g. for estuaries, bays, and lagoons. Others are dynamic in both time and space and difficult to define with precision; e.g., fluvial discharges and oceanic currents. Oceanic fronts and current patterns may help create quite different inner, middle, and outer shelf conditions, particularly over wide continental shelves.

2. Classification of Units

The description and typology (taxonomy) of the diversity of these units into ecosystem assemblages is the purpose of the proposed classification. Given the divisions and boundary conditions presented above, we may now identify the fundamental types of coastal units. Figure 3 demonstrates how a variety of assemblage types may be identified, and illustrates "simple, "compound," and "complex" types. For example, in a simple system, one tideland stream or estuary drains into the shoreface entrainment volume. In a compound type, multiple tideland streams drain into a common shoreface volume. In the former case, the longshore boundary includes only one drainage and in the latter case it includes more than one. A complex type possesses a large drainage that includes all three terrestrial compartments and has sufficient volume to bypass the shoreface volume; it drains more or less directly into the offshore volume. These are but three of the possible 16 assemblage types shown on the figure.

This scheme relates coastal unit size and complexity to hydrology. It allows a comparison among natural coastal units. The units vary greatly in size and complexity. This scheme results in a <u>hierarchical</u> <u>taxonomy</u> that orders coastal units in a logical and ecologically consistent way.

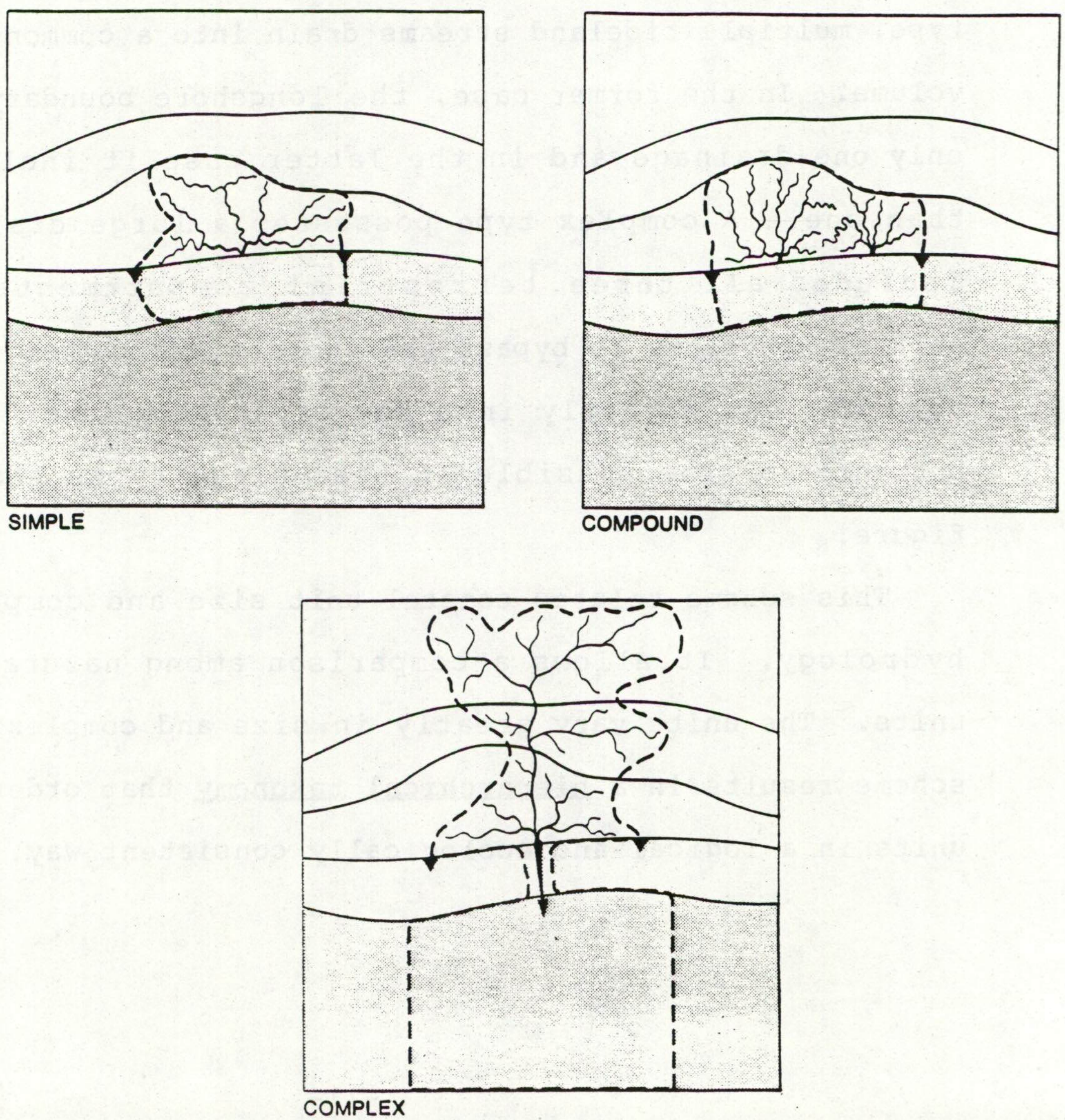
FIGURE 3

COASTAL UNIT TYPES

INLAND-MOST HEAD WATERS

ENTRAINMENT VOLUME	TIDELANDS	COASTAL PLAIN	UPLANDS
SHOREFACE	SIMPLE* COMPOUND*	SIMPLE COMPOUND COMPLEX	SIMPLE COMPOUND COMPLEX
OFFSHORE	SIMPLE COMPOUND	SIMPLE COMPOUND COMPLEX	SIMPLE COMPOUND COMPLEX*

* ILLUSTRATED



3. Controlling Processes

The coastal unit concept described above is essential for the development of fundamental mapping units within which habitats and biota can be included. The taxonomy of units may classify coastal ecosystem types on a map, but would be superficial without the incorporation of ecological processes, which we term "controlling processes," or simply "controls." The principal ones are given in table 4 and are physical, biotic, and human-related.

Controlling processes express the dynamics of ecosystems and can be used further to develop the taxonomy of environments. Some are straightforward, e.g., receiving basin morphology. Others are highly variable, e.g. climates. Biotic controls are conspicuous in tropical environments; witness the coral reef biota as major structural elements. Physical controls are more conspicuous at high latitudes; witness the influence of sea ice on coastal-marine environments. It is through the examination of controls that physical units can be differentiated latitudinally and among oceanic realms.

IV. METHODS

A. CARIBBEAN REGION

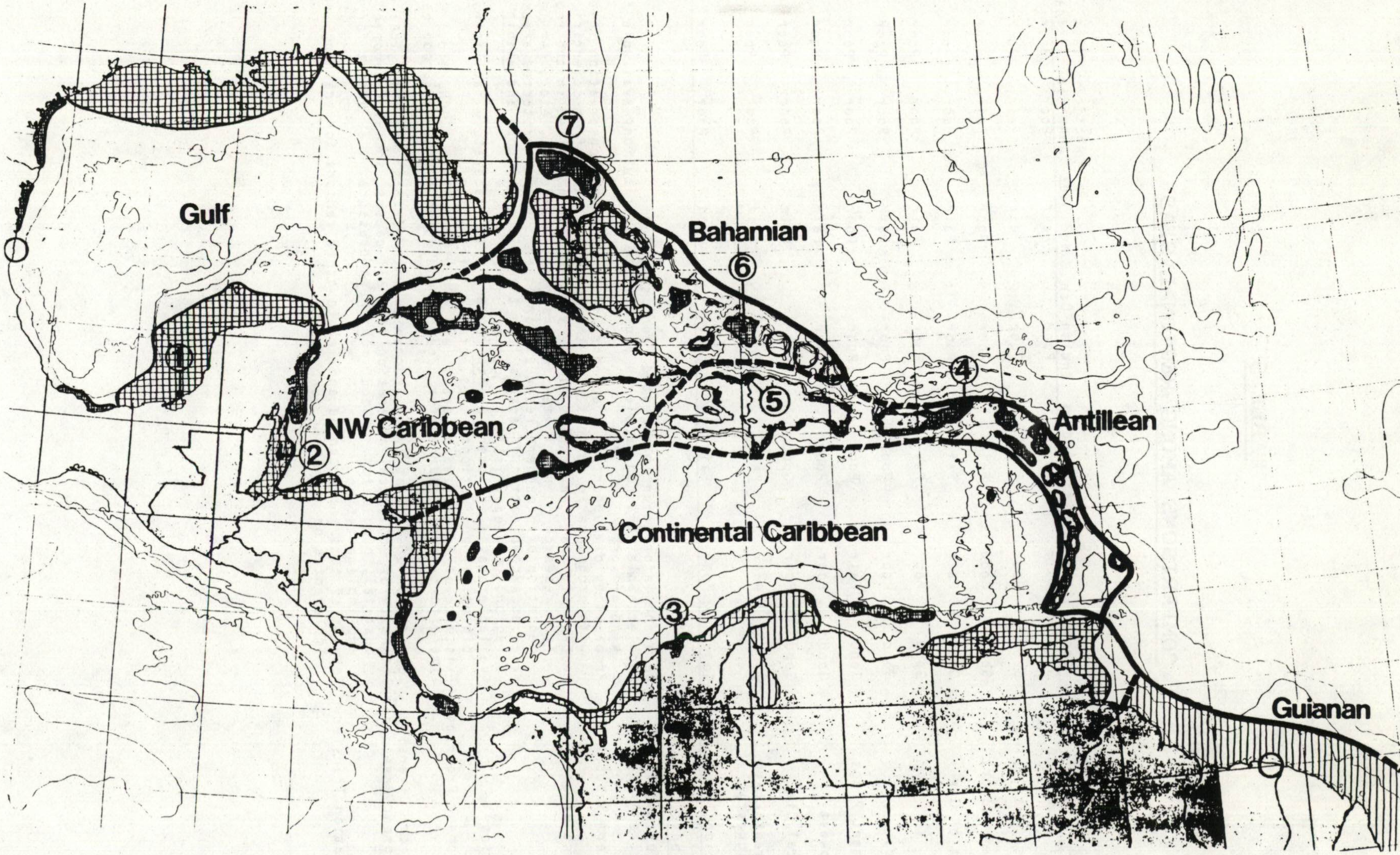
The Caribbean Region is well suited as an area in which to develop a coastal marine classification. Here we describe how we have divided it into subregions, and briefly characterize them.

1. Selection of Region

We have selected the Caribbean Region largely because of its rich data base, but also because of its physiographic diversity on a moderate geographic scale, plus practical considerations of access and transportation. Based on our comparisons of Regional Seas (table 5), the Caribbean represents the best available region for developing a coastal marine environmental classification. A few of these comparisons deserve special note.

The Caribbean Region (figure 4) has been defined operationally by the United Nations Environment Programme as a "Regional Sea". It extends from the Gulf of Mexico south to Guianas, and from Central America east to the Bahamas and Antilles; zoogeographically, it also includes Bermuda (Briggs, 1974). The Region covers 4,319 million square kilometers, with a sea water volume of 9,573 million cubic kilometers. It has a mean depth of 2,216 meters, and maximum depth of 7,539 meters (Kurian, 1983). Although the physical conditions of the region are diverse, the oceanographic and biotic features are not too unwieldy for the development of a classification system. The Caribbean Region is mostly composed of only one

FIGURE 4



THE CARIBBEAN REGION

Subregions of the Caribbean, after Ray et al (1979. We now propose subdividing the Antillean into Greater Antillean and Lesser Antillean, for a total of six subregions. See text for further explanation.

TABLE 5

COMPARISONS AMONG REGIONAL SEAS

	Caribbean	Oceania	Est. Indies	Indian Ocn.	Med. Sea	Arctic/ Anarctic	East Africa	West Africa
State of Knowledge	Good	Fair	Poor	Poor	Fair	Poor	Poor	Poor
Expertise Available	Good	Poor	Poor	Poor	Fair	Fair	Poor	Poor
Long-term Support	Good	Good	Fair	Poor	Poor	Fair	Poor	Poor
Prospect of Use	Good	Fair	Fair	Poor	Fair	Poor	Poor	Poor
Access	Good	Poor	Fair	Poor	Fair	Poor	Poor	Poor
Logistics	Good	Poor	Poor	Poor	Fair*	Poor	Poor	Poor
Development Progs.	Good	Fair	Poor	Poor	Poor	Poor	Poor	Poor
Cost (lowest)	Good	Poor	Poor	Poor	Fair	Poor	Poor	Poor
Ecological Div.	Good	Poor	Good	Poor	Fair	Poor	Poor	Poor
Development Press. (highest)	Good	Poor	Fair	Poor	Good	Poor	Poor	Poor
Information Trans.	Good	Poor	Fair	Poor	Good	Poor	Poor	Poor

Definitions:

State of Knowledge	Data and information in digested, published form.
Expertise Available	Knowledgeable, trained people in appropriate institutions available for this kind of work.
Long-term Support	Probability of support from appropriate development/conservation institutions with programmatic options over the long term; also from scientific programs.
Prospect of Use	Probability that the results of the study would be applied in the region, either from research point of view for training, monitoring, etc., for implementation of biosphere reserves (or other types of protected areas).
Access	Rated as a combination of access from the U.S. and Europe and within the region; (how easy is it to "get around"?)
Logistics	Available boats, equipment within region; also, laboratory facilities and biological collections, maps, etc. within region.
Development Programs	Existence of formailzed programs (e.g., UN, World Bank, IUCN, etc.)
Cost	Time/effort/funds required for conducting program from a US-Europe base and within region.
Ecological Diversity	Combination of habitat types, community interactions, and ecological processes.
Development Pressure	Intensity of ecological alteration from all causes, social, economic, industrial, population. "Good" = highest pressure, i.e. urgent for study and implementation.
Information Transfer	Results of this study can be applied to other regions for training, research, implementation and other purposes.

marginal sea and two major bodies of water, the Caribbean Sea proper and the Gulf of Mexico. The more complex East Indian Region, by contrast, contains 15 seas in the East Indian Archipelago area alone, and also includes the adjacent South China Sea, the Gulf of Thailand, the straits of Malacca, and the Burma Sea (Viglieri, 1966). The Indian Ocean contains eight seas. West Africa borders on two seas, and East Africa has three seas. Furthermore, for none of these more complex regions is data nearly as complete as for the Caribbean.

Nevertheless, the Caribbean region shares many similarities with other tropical regions of the world, and a classification based upon its features should be broadly applicable. It exhibits two dominant gradients; a west-to-east from continental-to-insular gradient, and a north-to-south from warm temperate-to-tropical gradient. It is characterized by westward currents associated with tradewinds, and is classified as an eastern tropical coastal margin realm (Hayden, Ray, and Dolan 1984). The East Indies, the Indian Ocean, and East Africa share the same general characteristics.

The Caribbean is physiographically diverse, and contains a large range of geologic structures that can be recognized in other regions, including volcanic mountains, submarine ridges, deep trenches, subterranean platforms, carbonate sandy cays, narrow and broad coastal shelves, and coral reef formations (both ancient and new). Unlike Oceania, it includes both continental and island systems of several types and sizes, with a habitat and biotic diversity that reflects both continental and oceanic influences.

2. Subregional Characteristics.

At least three marine biogeographic provinces (figure 1) are represented in the Caribbean Region, including the West Indian, Caribbean, and Louisianan (the latter is the Gulf of Mexico portion of the Carolinan Province, whose other segment lies along the Atlantic Coast of North America, outside of the Caribbean Region; Briggs, 1974). In this regard, it is moderately diverse compared to other tropical marine regions: Oceania contains only one large Province associated with the Pacific Plate (Springer, 1982), plus several complicated peripheral elements; the East Indies contains one province, and the Indian Ocean has five. All of these are more species-diverse than the Caribbean, and their biota is much less well known.

Ray et al. (1979) identified five subregions of the Caribbean, based on geology and climate, plus biogeographical features (figure 4). These five subregions were three continental marine subregions (the Gulf of Mexico, Northwest Caribbean, and continental Caribbean), and two insular subregions (Bahamian and Antillian). We now propose a subdivision of the Antilles into two subregions based on island size: the Greater Antillian subregion, containing the larger islands of Cuba, Hispaniola, Jamaica, and Puerto Rico, and the Lesser Antillian subregion, containing the smaller, more oceanic islands to the east. This separation is supported by the different geological origin, history and structure of the larger versus the smaller islands (Burke et al., 1984; Duncan and Hargraves, 1984; Pindell, 1985; Pindell and Dewer, 1982; Salvador and Green, 1980). The separation is also supported by work done in the preparation of this report, based on approximate distributions of coastal unit types.

The fauna of the three insular subregions together make up the West Indian zoogeographic province (Briggs, 1974). We anticipate that the proposed classification will distinguish these subregions zoogeographically for the same reasons it will distinguish them physiographically, i.e., differences in the distributions of coastal unit types will also produce differences in habitat and species distributions. Of the three insular subregions, the Lesser Antilles lacks an extensive coastal shelf; the Bahamian lacks the terrestrial influences of the nearly-continental habitats of the large islands, especially rivers.

Of the three continental subregions, the Gulf of Mexico is the most distinct in climate as well as in zoogeography; it is warm temperate rather than tropical (Briggs, 1974). We anticipate that it will also be distinguishable from the others physiographically and ecologically by the distribution of coastal units.

The resulting subdivision produces six subregions nested within three zoogeographic provinces, as follows:

West Indian Province	Bahamas Greater Antilles Lesser Antilles
Caribbean Province	Northwest Caribbean and Gulf of Mexico (part) Continental Caribbean
Louisianan	Gulf of Mexico (part)

B. CLASSIFICATION PROCESS

Here we describe the steps required for developing the Caribbean classification. The concept of coastal units, described above, is central to this procedure.

1. Spatial Scaling

The level of geographical resolution of the classification scheme will profoundly affect the results and their utilization. This research effort will focus on three levels of resolution. These are: 1) macroscale, representing the entire Caribbean region in six subregional components (map scale 1:2,000,000), and depicting the distribution of coastal unit types within the subregions; 2) mesoscale, at which individual coastal units are emphasized, representing interactions among units (map scale 1:200,000-250,000; and 3) microscale (map scale 1:20,000-24,000), representing local processes and habitat detail. These three levels are intended to comprise a hierarchical taxonomy of environments and processes.

The use of three scales is required in order to satisfy the combined requirements of generalizing over the entire region, yet also being specific in a local context. Risser (1986) points out that scaling contains two aspects: "1. Identifying and measuring processes that operate at two or more scales" and "2. Identifying general procedures for aggregating and disaggregating processes, models, data, and principles at different spatial and temporal scales." The use of different scales can be considered hierarchical and hierarchy theory can help solve scaling problems (Allen and Starr, 1982). Our methods, described below, address scaling by measuring similar features at all three scales. Temporal scaling problems will be addressed separately by this project through the use of predictive models (section V.C.).

2. Coastal Unit Analysis

This analysis will classify coastal ecosystems, based on structural (morphometric) characteristics of watersheds and adjacent seawater masses. Figure 3 shows a total of 16 possible "coastal units." Coastal units consist of as many as five compartments: three on the terrestrial side of the shoreline and two on the seaward side. Primarily, hydrologic linkages among the five compartments will be sought. Within oceanic areas, at least two more kinds of units can be recognized: oceanic basins and oceanic trenches.

The delineation of the coastal unit types and the distribution of coastal units in the region are mapping activities and are map-scale dependent. We propose analysis of coastal units at all three map scales mentioned above. The analysis at the macroscale will cover the entire region in six subregional maps (Gulf, Northwest Caribbean, Continental Caribbean, Bahamas, Greater Antilles, Lesser Antilles). At the macroscale, the distribution of coastal unit types will be apparent, and the boundaries of the larger coastal units will be delineated.

At the mesoscale, all but the smallest unit boundaries will be delineated on maps of selected portions of the six subregions. For example, all of the drainages of an island the size of Puerto Rico or Jamaica will be represented at this scale. We propose that the mesoscale maps be located to include established marine laboratories because of the availability of detailed local information they contain; laboratories participating in the UNESCO CARICOMP project would have priority. We suggest that the mesoscale maps be located along two major transects of the region, possibly including:

1) East-West Transect (continental-to-insular): Belize, Jamaica, Puerto Rico, Virgin Islands.

2) North-South Transect (Warm Temperate-to-Tropical): Florida WestCoast-Florida Keys, Bahamas, Barbados, Venezuela.

Maps of sites for analysis at the microscale will include habitat detail (such as marshes, reefs, mangroves, seagrass beds, sand shoals, etc.) of coastal units delineated on the mesoscale maps. Analysis at the meso and microscales will include detailed treatment of coastal unit morphometrics, that is, measurable attributes such as the width of the offshore entrainment volume, width and elevation of the upland compartments, tideland area, etc. At this scale, the linkages among coastal unit morphometrics, habitat types, and communities of species will be described. This species/habitat/coastal-unit, hierarchical classification is the central product of the project, and will allow the elements of predictive models for the region to be established. (Methods for establishing species-habitat linkages follow in the next section).

A data base adequate for this work is available in the form of topographic maps, bathymetric charts, Sailing Directions, satellite images, aerial photographs, museum collections and archives, and published technical reports. A modest field effort by project personnel will be required at the microscale sites.

3. Biodiversity and Habitat Relationships

a. Biodiversity.

Fishes will be the group of animals emphasized in establishing species-habitat linkages because they are important indicators of coastal and marine environmental types. They are also the best-collected of the animal groups in this region and others; in fact, many collections of Caribbean invertebrates were incidental to fish collections. Fish collections are very often quantitative, and reflect relative abundances of species to a greater extent than do invertebrate collections. Further, many fish species are known to be ecologically sensitive in that they have very specific environmental requirements. For example, a particular clinid blenny occurs only on reefs in pockets of coral rubble; a particular stargazer occurs only in calcium carbonate beaches where water bubbles up through the sand. Collectively, such species identify important subsets of habitat characteristics. Examples of habitat characteristics which act as controls on species distributions at the microscale level are sediment type (quartz versus calcium sands; muds, silts, clays), extent of seagrass beds, presence of shelter such as reefs or ledges; width of shelf; reef profile and extent of caves; surge and wave climate; water clarity; average temperature and annual temperature range.

Robins (1971) has described Caribbean fish distributions in general terms. All six subregions are well-collected, and the bulk of representative collections are at six locations: University of Miami, Florida State Museum at the University of Florida, the Field Museum in Chicago, American Museum of Natural History in New York, U.S. National Museum of Natural History, and Academy of Natural Sciences of Philadelphia. These collections are supported by a wealth of archival material in the form of field notes (in many cases, quite detailed) on habitat characteristics where individuals, species, and assemblages were taken. Two of the subregions (Louisianan and Bahamian) are also well-published. A major effort of project personnel will be devoted to establishing potential species-habitat linkages, especially for the four southern subregions, based on the expertise of project personnel and technical reports. Visits to the collections to modify and improve models will follow. Finally, analysis of species-habitat linkages, in the context of the mapping aspects of coastal unit analysis, will be performed.

b. Habitats.

At the same time, we will focus on three dominant habitat types of the Region: coral reefs, seagrass beds, and mangroves. This will involve analysis at all three spatial scales of the factors which affect habitat distribution, extent, and productivity, and especially the ecological linkages among them. For example, coral reefs are often cited as important ecological systems because of their high biotic productivity and diversity. But equally important in maintaining the populations of coral reef organisms, and often of greater importance in the support of commercially harvested species, are the seagrasses and mangroves.

Numerous studies have linked the abundance of commercial and sport fisheries to estuarine habitats, including seagrasses and mangroves (Odum, et al., 1982). In the U.S. portion of the Gulf of Mexico, about 70% of the recreational and 90% of the commercial fisheries are estuarine-dependent at some stage of their lives (Lindall and Saloman, 1977). Other studies have linked consumer abundance directly to seagrasses. In Rookery Bay, a mangrove-lined estuary, seagrasses covered substantially less than 20% of the estuary bottom, but accounted for 77% of the total catch of fish, crustacea, and mollusks, and over 82% of the commercial shrimp catch was taken there (Yokel, 1975). This abundance in seagrass meadows has been found widely (Hooks et al., 1976; Carter et al., 1973).

The interdependence of coral reef, seagrass, and mangrove ecosystems is nowhere more obvious than in the Caribbean (Ogden and Gladfelter, 1983). Here, the coral reefs shelter vast numbers of fishes during the day, but by night, many fishes migrate to seagrass beds to feed. Thus, the seagrass community represents a feeding ground for many coral reef organisms, which transfer nutrients and biomass to the reef. Other species found on the reefs as adults require the nursery habitat of mangroves or seagrasses as juveniles; where either habitat is lacking locally, so are such species. The need to understand the interrelationships among these major coastal systems, as well as the factors controlling productivity in the Caribbean coastal zone, has led to the founding of the CARICOMP program by UNESCO, with which we intend to collaborate.

4. "Potential Distribution" Analysis.

The most common type of geographic information on species presence or absence is the range map. Range maps are constructed from decades of natural history surveys and other forms of written records. Range maps only set the boundaries of species' occurrence; they do not give actual distributions. True distribution maps of marine species, based on detailed surveys, are uncommon. We will archive range maps of species for the Caribbean region in a geograpic information system

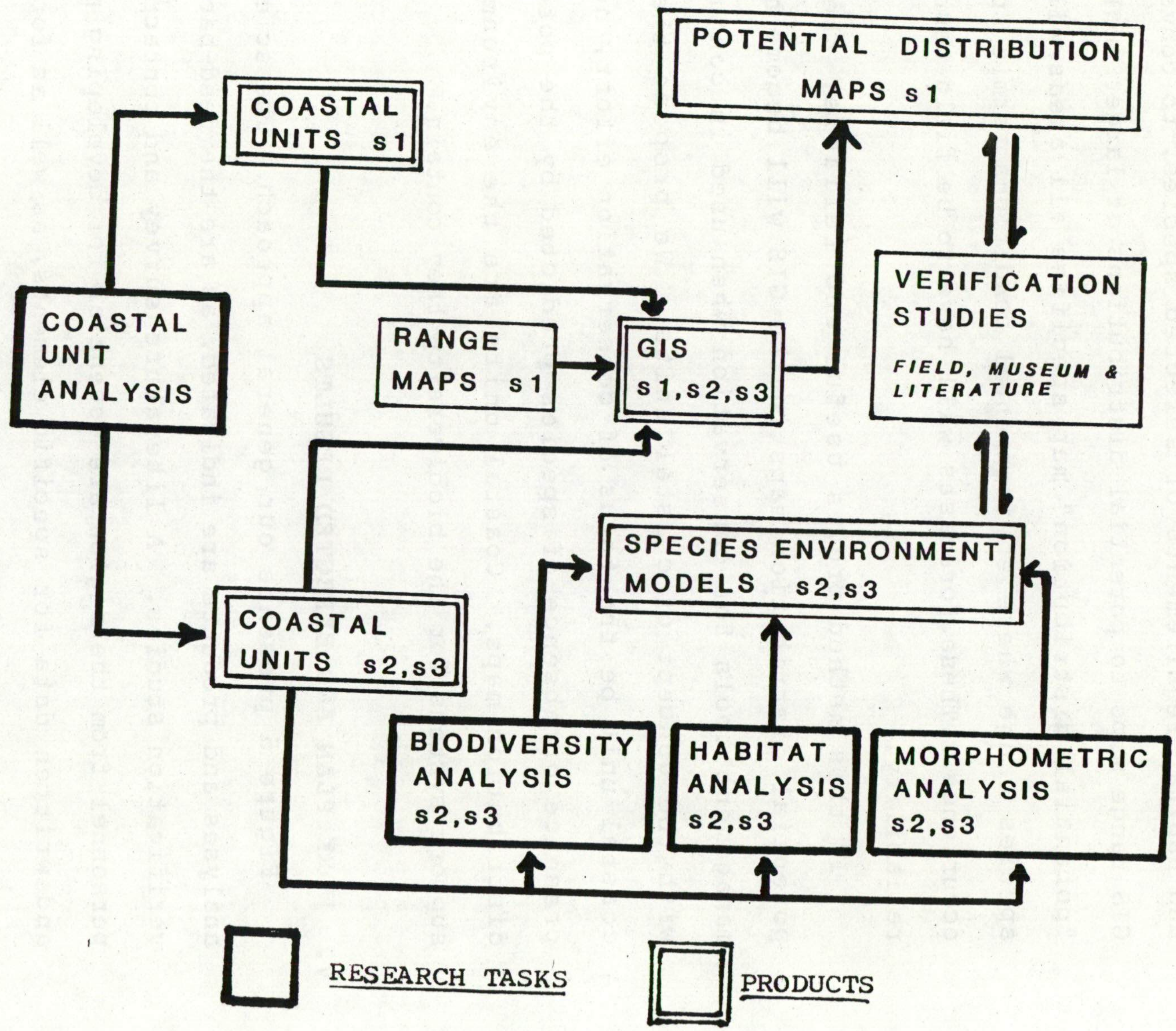
(GIS - see below). We will then use a morphometric analysis of coastal units at a small scale, with the natural histories and habitat requirements of selected species, to convert the GIS range maps to potential distributions at larger scales. A "potential distribution" map specifies all areas within a species range where environmental conditions permit species' occurrence. These forecasts will have to be field tested for reliability.

If this method proves useful and reliable, then the potential distribution maps in the GIS will become helpful management tools for conservation when used in conjunction with the concept of coastal units. We propose that the coastal unit be the focus of conservation effort, not the presence or absence of species predicted by the potential distribution maps. Coastal units are the environmental support systems for the biodiversity they contain.

V. WORK PLAN AND EXPECTED RESULTS

Figure 5 presents our general approach. The scientific analyses and products are indicated, as are the feed-backs and verification studies. A literature survey and contacts with personnel from the region are essential for developing mapped and written data for specific elements, as well as for later implementation of the results of this project. This will be further promulgated through the incorporation of a training component in this project: for example, seminars, short-term scholarhips, and graduate students from the region. At the

FIGURE 5



COASTAL UNIT ANALYSIS
COASTAL UNITS s1
COASTAL UNITS s2,s3
RANGE MAPS s1
GIS s1,s2,s3
POTENTIAL DISTRIBUTION MAPS s1
VERIFICATION STUDIES
FIELD, MUSEUM & LITERATURE
SPECIES ENVIRONMENT MODELS s2,s3
BIODIVERSITY ANALYSIS s2,s3
HABITAT ANALYSIS s2,s3
MORPHOMETRIC ANALYSIS s2,s3
RESEARCH TASKS
PRODUCTS

beginning of the each year of work, a week-long workshop among the principals of this project and collaborators in the Caribbean will be held in the region to elaborate methods to re-evaluate the conceptual basis for work, and to examine results achieved so far.

During the first year, the following will be accomplished: (1) determine the list of elements to be examined during the course of the entire project; (2) work out details of data entry, retrieval, and formatting; (3) establish a grid system for data management; (4) develop sample maps and design sample surveys; (5) develop preliminary ecological models for data analysis, and (6) produce six subregional maps showing the distribution of coastal unit types in the entire region. With these in hand we will proceed in the manner of the diagram, using "feed-backs" between the initial and later phases of work. Products are provided at several stages in the form of computer maps and data summaries that are improved through field survey efforts.

Analyses will take a number of forms, as described in Section IV.B. The results will be in the form of descriptions of the ecological organization of coastal units. At almost any point, an "atlas" of computer-generated data and information can be provided at low cost, through use of the retrieval system established at the project's outset (and subject to modification as experience demands).

Models will be developed to associate physical features, processes, and species distribution. Models will express the mobility, dynamism, successional states, and responses to short-term events (e.g. storms) that are characteristic of coastal and marine systems.

The work plan is based on the assumption that the full project can be projected for funding from the outset. Administration must be straightforward and reporting based primarily on the need to communicate among principals. A further assumption is that funding will be implemented through UNESCO and IUCN, with the aid of collaborating organizations; for example, NASA and various other international agencies.

A. PRODUCTS

The work plan, above, has described our proposed procedures. Figure 5 indicates that products result from each stage of the work at approximately annual intervals. Specifically, these products are as follows:

Year 1: We will produce six macroscale coastal unit maps (1:2,000,000) of the entire Caribbean region, delineating major coastal units and major characteristic physiographic features of the adjacent oceanic areas (e.g. trenches). We will also produce preliminary physiographic maps at mesoscale (1:200-250,000) and microscale (1:20,24,000). An accompanying text will explain the maps. In addition, we will describe in detail, by the end of the first 6 months of this year, the work plan for field research for Year 2.

Year 2: The products of field research will be described, including the museum work on fishes (section IV.B.3). Refined maps at meso and microscales will also be produced. Each of these products will be accompanied by an explanatory text. Models will be developed to explain species/habitat relationships, and these will be included in the text.

Year 3: By the end of this year, the meso and microscale maps indicating habitats and fish diversity will be produced with accompanying text. In addition, macroscale maps of the entire region, showing potential habitat and fish relationships will be included, as will a few sample ecological models (see below). These will be in the form of a FINAL REPORT, which will also describe how the classification can be applied to other regional seas. All data and analyses will be included in a GIS, with guidelines for its use, for further analyses and for demonstrations in the Caribbean and elsewhere. The report will provide a rigorous scientific basis for selection of candidate biosphere reserves in the Caribbean, with guidelines for their management.

B. GEOGRAPHICAL INFORMATION SYSTEM (GIS)

The formidable complexity of regional coasts and seas and the volume of data that can be accumulated requires simplicity of procedures and substantial power of summary. Consequently, both raw data and derived information will be incorporated into the **geographic information system** that can be used within the Caribbean Region at relatively low cost.

Thus, we do not propose an "inventory" in the usual, exhaustive sense, since this is too time-consuming, costly, and impractical, nor the production of atlases, which are static and dated almost as soon as they are produced. The GIS will involve: a computer program for data entry and retrieval; analytical tools for deriving classes of information; models for prediction of temporal changes; and updating of data through continuing monitoring.

GIS's are increasingly being used for analyses of large, complex, geographic data sets. The features of geographic information systems are well known (e.g. Risser and Treworgy, 1985); geographic mapping ability, retrieval of data through simple program commands, rapid cross-referencing of spatial and subject data, capability of handling data at different scales, and great flexibility. The GIS system will be portable, for training and demonstration purposes.

C. PREDICTVE MODELLING: TEMPORAL GIS COMPONENTS

Models serve best to integrate the data described above. Our mapped products will show the spatial diversity of the Caribbean. However, temporal changes are also important. One example model is described here, for mangroves. The proposed work will also ensure that data are available for modelling coral reef and seagrass habitats.

Mangrove ecosysystem development (aerial extent, stand height, etc.) may be related to the series of physical parameters and resulting classification outlined elsewhere in the proposal. This in turn can be related to occurrence of animal and plant species which are dependent upon mangrove swamps as habitat (including some rare and endangered species). Finally, the role of periodic disturbance (particularly regular hurricane reoccurrence) in structuring and altering mangrove ecosystems can be predicted.

MANGRO is a computer simulation model of mangrove forests. Similar models have applied successfully to forests around the world to predict the effects of fires, storm, management methods, and climate change (for example, see Shugart, 1874). Currently the mangrove model includes 3 species: Rhizophora, Avicennia, and Languncularia. MANGRO models the forest by mathematically simulating the growth and competitive interactions of each of the individual trees comprising the forest. Growth rates of the trees are based on known physiological properties of each species, e.g. maximum growth rate, salt tolerance, shade tolerance, responses to tides, etc. Trees "compete" for light in the model, and those individuals that do not receive enough light are eliminated from the simulation ("die"). Trees only enter the simulation ("germinate") when environmental conditions are appropriate, based on what is known of their germination requirements. The model is of a size and complexity that allows it to be used on a personal computer.

Because MANGRO is a dynamic model based on the natural history and physiology of individual trees according to size and species, it can predict the response of forests to changing environmental conditions. The model can incorporate a range of ecological, environmental features, including:

- Effect of altered salinity and tidal amplitude, or added pollution stress on species composition and productivity;

- Stem diameter, total biomass, root biomass, stem biomass, leaf biomass and leaf area;

- Nutrient and energy content of leaves, seeds, shed root material, etc.;

- Decomposition rates and transport of organic matter in relation to salinity, tides, etc.;

- Population size of mangrove consumer species (shrimp, fish, etc.) in relation to mangrove biomass, productivity, litterfall, root area, or other relevant parameters; and

- Wood strength, susceptibility to wind and wave damage, effects of storms of known intensity.

VI. PERSONNEL AND BUDGET

A. PERSONNEL

1. University of Virginia

   Arthur J. Bulger, Visiting Scholar -- FISHES
   Bruce P. Hayden, Professor -- GEOMORPHOLOGY, <u>Co-Principal</u>
   M. Geraldine McCormick-Ray, Research Scientist -- POLLUTION, STRESS
   William Odum, Professor -- MARSHES, MANGROVES
   Herman H. Shugart, Professor -- MODELLING
   G. Carleton Ray, Research Professor -- MARINE ECOLOGY, <u>Co-Principal</u>
   David E. Smith, Res. Asst. Professor -- BIOLOGICAL OCEANOGRAPHY
   Joseph C. Zieman, Associate Professor -- SEAGRASSES, REEFS

2. University of Miami

   C. Richard Robins, Professor -- FISHES, MARINE ECOLOGY

<u>Note</u>: This team will be augmented by research assistants, graduate students, and trainees, as required.

B. BUDGET:

This budget is a best estimate. It is for the full three years duration of the project. The levels of effort among years is not equal: the first year will take approximately 25% of the budget, the second year about 45% due to the expense of field work, and the third year 30%.

1. Personnel	
a. Faculty (approximately 60 man-months)	$240,000
b. Students, assistants, etc.	100,000
2. Fringe benefits	50,000
3. Consultants (regional)	20,000
4. Travel	
a. Personnel	30,000
b. Field costs (boats, etc.)	40,000
5. Contractural Services (computing, cartography, etc.)	5,000
6. Supplies (maps, film, etc.)	10,000
7. Equipment -- demonstration computer for GIS	5,000
TOTAL DIRECT COSTS	$500,000

Note: This budget <u>does not include indirect costs</u>, which will be negotiated, depending on funding sources, etc. <u>Nor does it include costs of personnel from the region</u> who will be collaborating on this project; some consulting funds are included to cover some of the costs. Costs of personnel from the region will be ascertained during the first year's regional workshop.

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