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NOAA Coastal Change Analysis Program (C-CAP): Guidance for Regional Implementation

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Preface

This unique document represents a first attempt to develop guidelines that will allow researchers and resource managers alike to quantitatively monitor changes that are occurring in the abundance of emergent and submergent wetlands and adjacent uplands in coastal regions. Such information is essential in order to effectively relate changes in coastal land use to changes in the productivity of estuaries and coastal waters on a regional scale.

This is a document that was developed from the input of approximately 200 research scientists and resource managers that attended five regional workshops and several topical interagency meetings. Thus, we believe it represents a general consensus of how to approach the issue of quantifying land-cover and wetland change in coastal regions. Because improvement in existing technologies and in our understanding of how to measure habitat change on a regional scale undoubtedly will occur, we intend to update this document periodically. These updates, however, require time to publish, so anyone planning to use these guidelines should contact either the senior author or program manager to obtain drafts of any revised chapters that have not yet been published.

Finally, I would like to express my appreciation to the authors for their fine effort and to Dr. Don Scavia, Director of NOAA's Coastal Ocean Program, for his support, both financial and moral, during the development of this document. I believe we have made a significant step in addressing an important coastal issue.

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Executive Summary

The Coastal Change Analysis Program[1] (C-CAP) is developing a nationally standardized database on land-cover and habitat change in the coastal regions of the United States. C-CAP is part of the Estuarine Habitat Program (EHP) of NOAA's Coastal Ocean Program (COP). C-CAP inventories coastal submersed habitats, wetland habitats, and adjacent uplands and monitors changes in these habitats on a one- to five-year cycle. This type of information and frequency of detection are required to improve scientific understanding of the linkages of coastal and submersed wetland habitats with adjacent uplands and with the distribution, abundance, and health of living marine resources. The monitoring cycle will vary according to the rate and magnitude of change in each geographic region. Satellite imagery (primarily Landsat Thematic Mapper), aerial photography, and field data are interpreted, classified, analyzed, and integrated with other digital data in a geographic information system (GIS). The resulting land-cover change databases are disseminated in digital form for use by anyone wishing to conduct geographic analysis in the completed regions.

C-CAP spatial information on coastal change will be input to EHP conceptual and predictive models to support coastal resource policy planning and analysis. C-CAP products will include 1) spatially registered digital databases and images, 2) tabular summaries by state, county, and hydrologic unit, and 3) documentation. Aggregations to larger areas (representing habitats, wildlife refuges, or management districts) will be provided on a case-by-case basis. Ongoing C-CAP research will continue to explore techniques for remote determination of biomass, productivity, and functional status of wetlands and will evaluate new technologies (e.g. remote sensor systems, global positioning systems, image processing algorithms) as they become available. Selected hardcopy land-cover change maps will be produced at local (1:24,000) to regional scales (1:500,000) for distribution. Digital land-cover change data will be provided to users for the cost of reproduction.

Much of the guidance contained in this document was developed through a series of professional workshops and interagency meetings that focused on a) coastal wetlands and uplands; b) coastal submersed habitat including aquatic beds; c) user needs; d) regional issues; e) classification schemes; f) change detection techniques; and g) data quality. Invited participants included technical and regional experts and representatives of key State and Federal organizations. Coastal habitat managers and researchers were given an opportunity for review and comment.

This document summarizes C-CAP protocols and procedures that are to be used by scientists throughout the United States to develop consistent and reliable coastal change information for input to the C-CAP nationwide database. It also provides useful guidelines for contributors working on related projects. It is considered a working document subject to periodic review and revision.

[1] Formerly known as the "Coast Watch Change Analysis Project."

Chapter 1
Introduction

The Coastal Region Management Problem

The conterminous United States lost 53 percent of its wetlands to agricultural, residential, and commercial land use from the 1780's to 1980's (Dahl, 1990). Oil spills occurring throughout the world continue to devastate coastal wetlands (Jensen et al., 1990; Narumalani et al., 1993). Sea level has risen approximately 130 m in the past 17,500 years. More abundant "greenhouse" gases in the atmosphere may be increasing the Earth's average temperature (Clarke and Primus, 1990) and may, yet again, accelerate the global sea level rise, eventually inundating much of today's coastal wetlands (Lee et al., 1992). Unfortunately, current projections for U.S. population growth in coastal regions suggest accelerating losses of wetlands and adjacent habitats, as waste loads and competition for limited space and resources increase (U.S. Congress, 1989). Coastal wetlands and submersed habitats are being destroyed by erosion, dredge and fill, impoundments, toxic pollutants, eutrophication, and (for submersed habitats) excessive turbidity and sedimentation. Many marine finfish and shellfish depend on these coastal habitats for their survival. Salt marsh grasses, mangroves, macroalgae, and submersed grasses and forbs are essential as nourishment and animal habitat. Continued loss of these wetlands may lead to the collapse of coastal ecosystems and associated fisheries. Documentation of the loss or gain of coastal wetlands is needed for their conservation and effective managment of marine fisheries (Haddad and Ekberg, 1987; Haddad and McGarry, 1989; Kiraly et al., 1990; Kean et al.[1]).

Submersed grasses and forbs include seagrasses that require high salinity and other species of submersed rooted vascular plants (SRV) that tolerate or require low salinity water. Submersed grasses and forbs may be crucial indicators of water quality and overall health of coastal ecosystems (Dennison et al., 1993). Submersed vegetation has the additional requirement of living at photic depths and therefore is particularly sensitive to water clarity (Kenworthy and Haunert, 1991). Change (increase or decrease in areal extent, movement, consolidation or fragmentation, or qualitative change) in submersed habitat may be a sensitive integrator of overall water quality and potential for change in fisheries productivity. Submersed rooted vascular aquatic beds define habitat critical for the support of many recreational and sport fisheries (Ferguson et al., 1980; Zieman, 1982; Phillips, 1984; Thayer et al., 1984; Zieman and Zieman, 1989; Klemas et al., 1993). Changes in uplands, wetlands, and submersed habitats can be rapid and pervasive. Hence, effective management requires frequent monitoring of coastal regions (at least twice per decade).

It has long been suspected that a crucial factor in the observed decline of fisheries in most coastal regions is the declining quantity and quality of habitat. Land-cover change is a direct measure of quantitative habitat loss or gain. For many marine fisheries the habitats (i.e. land covers) of greatest importance are saltmarsh and seagrass. Other fisheries, such as those for salmon, depend on a variety of habitats that may include upland as well. Land-cover change is also a direct measure of increases or decreases in sources of pollution, sedimentation, and other factors that determine habitat quality. Increases in developed land, for example, are accompanied by land disturbance that increases erosion and sedimentation and by hydrologic alteration that increases runoff. Similarly, cultivated land is associated with fertilizer and pesticide use that ultimately affects the marine environment. Hence, land-cover change is linked to habitat quantity and quality.

The NOAA Coastal Change Analysis Program (C-CAP) Solution

For these reasons, the National Oceanic and Atmospheric Administration (NOAA) Coastal Ocean Program initiated the Coastal Change Analysis Program (C-CAP), a cooperative interagency, State, and Federal effort to detect coastal upland and wetland land cover and submersed vegetation and to monitor change in the coastal region of the United States (Cross and Thomas, 1992; Haddad, 1992). The project uses digital remote sensor data, in situ measurement in conjunction with global positioning systems (GPS), and geographic information system (GIS) technology to monitor changes in coastal wetland habitats and adjacent uplands. Landsat multispectral scanner (MSS) data, Landsat Thematic Mapper (TM) data, and SPOT high resolution visible (HRV) data have been used success-

[1] Kean, T. H., C. Campbell, B. Gardner, and W. K. Reilly. 1988. Protecting America's wetlands: an action agenda. Final Report of the National Wetlands Policy Forum. The Conservation Foundation, Washington, D.C.

fully to detect major categories of wetlands (Haddad and Harris, 1985; Jensen et al., 1993b; Lade et al.[2]). However, they have not been used previously to map or monitor wetlands for regional or national coverage. The use of satellite imagery for mapping wetlands provides a number of advantages over conventional aerial photographs including timeliness, synopticity, and reduced costs. While aerial photography may be appropriate for high resolution cartography, satellite imagery is better suited and less costly for rapid, repeated observations over broad regions (Haddad and Harris, 1985; Bartlett, 1987; Klemas and Hardisky, 1987; Ferguson et al., 1993). Although the program will stress the use of satellite imagery, particularly for coastal wetlands and adjacent uplands, aerial photography or a combination of photography and satellite imagery (TM or SPOT) will be used for mapping SRV (Orth and Moore, 1983) and certain other habitats, as suggested by Patterson (1986) and Lade et al. (1988). A methodology to photographically observe, analyze, and display spatial change in habitat defined by the presence of SRV was a prerequisite to a nationwide change detection effort (Thomas and Ferguson, 1990).

The C-CAP nationally standardized database will be used to monitor land-cover and habitat change in the coastal regions of the United States (Thomas and Ferguson, 1990; Thomas et al. 1991) and to improve understanding of coastal uplands, wetlands (e.g. salt marshes), and submersed habitats (e.g. seagrass) and their linkages with the distribution, abundance, and health of living marine resources. Coastal regions of the U.S. will be monitored every one to five years depending on the anticipated rate and magnitude of change in each region and the availability of suitable remote sensing and in situ measurements. This monitoring cycle will provide feedback to habitat managers on the success or failure of habitat management policies and programs. Frequent feedback to managers will enhance the continued integrity or recovery of coastal ecosystems and the attendant productivity and health of fish and other living marine resources at minimal cost. In addition, the geographical database will allow managers and scientists to evaluate and, ultimately, to predict cumulative direct and indirect effects of coastal development on wetland habitats and living marine resources. Initially, C-CAP products will document current land-cover distribution and change that have occurred in the recent past. The database, as it increases with each subsequent monitoring cycle, will be an invaluable baseline resource for research, evaluation of local, State, and Federal wetland management strategies, and construction of predictive models. C-CAP directly supports NOAA's responsibilities in estuarine and marine science, monitoring, and management as legislated in the Fish and Wildlife Coordination Act; the Magnuson Fishery Conservation and Management Act; the Coastal Zone Management Act; the Clean Water Act; the Marine Protection, Research, and Sanctuaries Act; and the National Environmental Policy Act. Land-cover change data are essential to the implementation of a "No Net Loss" wetlands policy.

A large community of managers, scientists, and users were involved in developing a C-CAP protocol at the national level. Guidance in this document was derived from a series of professional workshops and interagency working group meetings which focused on

- user needs
- upland, wetland, and water classification schemes
- regional boundary issues
- cartographic datum and data structures
- selection of appropriate satellite imagery and aerial photography
- field work and field verification methods
- satellite remote sensing of coastal wetlands and uplands
- photo interpretation of coastal submersed habitat, including seagrasses
- calibration among regions and scenes
- classification and change detection algorithms
- geographic information processing and analysis
- regional ecological modeling
- quality assurance and control
- product availability and distribution
- research issues

Approximately 40 scientists and environmental managers attended each major regional workshop held in the Southeast, Northeast, Pacific Coast, and Great Lakes regions; about 200 individuals participated in all workshops and special meetings. The community of users and providers of coastal habitat information were given an opportunity for review and comment. A detailed list of workshops is provided in Appendix 4.

Although C-CAP is national in scope, it is based on procedures also applicable at local and regional levels. Much of the content of this document is based on C-CAP sponsored research conducted at the regional level. For example, Klemas et al. (1993) of the College of Marine Studies at the University of Delaware developed the "C-CAP Coastal Land Cover Classification System" by investigating existing upland and wetland classification systems and then synthesizing a new system that is practical at the regional level. Dobson and Bright (1991, 1992, and 1993) of the Oak Ridge National

[2] Lade, P. K., D. Case, J. French, and H. Reed. 1988. Delineation and classification of submerged aquatic vegetation using SPOT satellite multispectral digital data. Final report to the Maryland Dept. Natural Resources, Tidewater Administration, Coastal Resources Div., Annapolis, MD.

Laboratory (ORNL) developed a regional prototype to inventory uplands and wetlands in the Chesapeake Bay region. Jensen et al. (1993a) evaluated various change detection algorithms for inland and coastal wetland environments near Charleston, S. C. Ferguson et al. (1993) developed a regional prototype to inventory SRV in North Carolina based on protocols developed by the Beaufort Laboratory, Southeast Fisheries Science Center, National Marine Fisheries Service (NMFS). Khorram et al. (1992) investigated methods of seamlessly integrating multiple-region C-CAP databases.

The C-CAP protocol continues to evolve and improve. For example, projects underway in 1993 include analysis of the effects of tidal stage on remote-sensing classification, change detection accuracy assessment, refined techniques for classification of forested wetlands, and advanced change detection techniques (Appendix 5). Research continues on functional health indicators (e.g. biomass, productivity), plant stress (e.g. mangrove freeze), new data-collection instruments, and regional ecological modeling. Thus, C-CAP will continue to have a strong research and development component to improve and refine its operational techniques.

National Scope and Regional Implementation of C-CAP

No single Federal or State organization will collect all the information residing in the C-CAP database. Instead, regional inventories will be completed by regional experts following C-CAP guidelines. Therefore, it is important to define the logic used to specify a C-CAP region. First, regional boundaries must coincide with the following NOAA/NMFS regions:

Northeast — Virginia through Maine, including the Great Lakes
Southeast — Texas through North Carolina, U.S. Virgin Islands, and Puerto Rico
Northwest — Oregon, Washington, and Alaska
Southwest — California, Hawaii, Midway Islands, Wake, Guam, Mariana Islands, American Samoa, Johnston Atoll, Trust Territory of the Pacific Islands, Baker and Howland Islands, and Jarvis Island.

Coastal regions may be further subdivided, as appropriate, on the basis of State and other administrative boundaries or ecoregions as defined, for example, by Omernik (1987).

The boundary should encompass coastal watersheds plus offshore coral reefs, algae, and seagrass beds in the photic zone. In keeping with the goals of C-CAP and anticipated funding constraints, the recommended approach is to designate 1) standard coverage limits for general application and 2) extended coverage limits for regions with special needs. Standard coverage will utilize biological and other geographical boundaries appropriate to the needs of specified C-CAP users identified through the protocol workshops. Extended coverage will be defined for each regional project in collaboration with states and other regional organizations. NOAA will make every effort to identify and accommodate research, conservation, management, and the needs of other interests that rely on wetland maps and data. Regional projects will be designed to identify special needs that may require extended coverage and to suggest sources of funds to support the additional cost of extended coverage.

The estuarine drainage area (EDA), defined by NOAA's National Ocean Service (NOS) as the "land and water component of an entire watershed that most directly affects an estuary," is an appropriate standard coverage area for C-CAP. For the purposes of this program, all U.S. coasts are or will be defined as part of an EDA. The boundary of each EDA basin is defined to be consistent with U.S. Geological Survey (USGS) hydrologic units and codes.

The estuarine drainage boundary as defined by NOS is considered a standard inland boundary for C-CAP regional projects. Regional analysts may employ C-CAP protocols upstream, but C-CAP funding is not intended for coverage beyond the EDA. However, C-CAP funding may be used to purchase satellite scenes that extend beyond the EDA if they are necessary to cover the coastal region. Functional definitions, such as "limits of tidal influence," may be employed in response to local situations justified by local user communities and local or regional experts on a coastal region-by-region or estuary-by-estuary basis. Regional analysts should be aware of local, State, and Federal rights and responsibilities and should seek intergovernmental and interagency cooperation. Because C-CAP interests include the effects of eutrophication due to development of uplands, information from outside the EDA may be justified in high order streams that extend beyond the coastal region. In this case, the point where the river enters the region will be defined as a point source for inputs.

The offshore boundary of each region is defined as the seaward extent of wetlands, seagrass, coral, or other submersed habitat detectable using remote sensing systems. The functional definition of limits of detection normally will be based on satellite and aerial sensors and will vary within and among regions. Both the limits of detection and the actual bathymetric range of SRV are based on light attenuation and, thus, will not be a consistent bathymetric contour even within a single region.

Overlap of regions, consistent with TM scene boundary overlap, is preferred so that analysts may calibrate results from neighboring regions. A healthy exchange between neighboring regional analysts could reconcile differences, not only in the area of overlap, but also in signature identification across both regions. Each regional project team will be responsible for calibrating the relationship between remotely sensed spectral information and other information such as field measurements of biomass and photosynthetic rates. Historically, such measurements have focused on relatively few of the many species, habitats, and land-cover types of significance in the coastal region. Analysts should also ensure that protocols originally developed for northern temperate latitudes are modified sufficiently to serve well in tropical areas of the southern United States, Caribbean, and Pacific Ocean, and in the Arctic areas of Alaska. It will be necessary, for example, to use different methods and sensors for coral reefs than for wetlands. Similarly, the identification of Arctic muskeg may require different methods and sensors from those used to identify temperate, herbaceous wetland.

Change Detection Every One to Five Years

The frequency of change detection is a crucial issue. For most regions in the United States, the base year (referred to as T_b or Date 1 in the diagrams) should be the most recent year for which acceptable satellite imagery for uplands and wetlands or aerial photographs for submersed habitat can be obtained, and for which sufficient in situ information is available to conduct an error evaluation. Exceptions may occur in regions where cloud cover is a perennial problem or where other considerations favor aerial photographs over satellite imagery. The choice of the second date of imagery (Date b–1 or b+1) may be more flexible. It may be desirable to choose a date one to five years earlier than the base period to capture recent changes in coastal habitats. Plans should then be made for another change analysis no later than five years after the base time. However, plans may be altered abruptly when natural or human-induced events, such as hurricanes and oil spills, occur.

Five years is the recommended frequency of change detection for most regions, but shorter periods may be necessary in regions undergoing rapid economic development or affected by catastrophic events. Longer periods may be necessary where funds are limited or where change is exceptionally slow. Regional analysts are advised to evaluate rates of change and explicitly recommend the base year and change period as a part of each regional project proposal. Unfortunately, remotely sensed data obtained specifically for other purposes (e.g. urban analysis, forest inventory) often are not suitable for use in C-CAP. Aquatic beds, and even coastal wetlands, may not be identifiable on aerial photographs obtained for other purposes.

The Need for Standardization and Guidelines

C-CAP desires to create a synoptic, digital database of coastal wetland and upland land cover by class for a base time period and to identify change between the base period and other time periods. The use of satellite remote sensing to inventory uplands and wetlands, conventional aerial photography to inventory submerged lands, and GIS to analyze the data are important elements of the C-CAP methodology. However, the goal of completing an accurate change detection product overrides any given technical consideration. Therefore, timely high-quality information from aerial photographs, topographic maps, field experience, or other sources may be used to prepare C-CAP products if appropriate guidelines are followed.

By standardizing procedures at the national level, this document will benefit not only C-CAP but also coastal management research conducted by other State and Federal agencies. C-CAP desires to facilitate the exchange of standardized data among programs, decrease duplication, and improve the quality and utility of decision support for wetlands policy, management, and research activities. All data accepted for inclusion and eventual distribution in the C-CAP database must adhere to the protocol described in this manual. The protocol is designed to allow flexibility in the use of elements of the classification scheme and in the choice of remote sensor data, classification and change detection procedures, and other key elements that vary regionally. However, potential users must adhere to the protocol in order to maintain high quality information in the C-CAP database. Coastal land-cover change databases derived independently from C-CAP will be considered for dissemination as C-CAP products if originating organizations can document compliance with C-CAP protocol and data quality standards.

General Steps Required to Conduct Regional C-CAP Projects

The general steps required to conduct regional C-CAP change detection projects using satellite remotely sensed data are summarized in Table 1. This document is organized according to these specific requirements and, in certain instances, provides step-by-step instructions to be used when conducting regional projects. One of the first requirements of regional participants is to precisely identify land-cover classes of interest to be monitored and eventually placed in the C-CAP change detection database. This must be performed in conjunction with an appropriate classification scheme. Unfortunately, no existing standardized classification scheme was suitable for all C-CAP requirements. Therefore, great effort went into the development of the C-CAP Coastal Land-Cover Classification System, which can be used to inventory uplands and wetlands by using satellite remote sensor data and to inventory SRV by using metric aerial photography.

Table 1

General steps required to conduct regional C-CAP change detection projects to extract upland and wetland information using satellite remote sensing systems. Each major step is listed in the order to be accomplished.

1. **State the regional change detection problem**
   a. Define the region
   b. Specify frequency of change detection (1 to 5 yr)
   c. Identify classes of the C-CAP Coastal Land-Cover Classification System

2. **Consider significant factors when performing change detection**
   a. Remote sensing system considerations
      1) Temporal resolution
      2) Spatial resolution
      3) Spectral resolution
      4) Radiometric resolution
      5) The preferred C-CAP remote sensing system
   b. Environmental considerations
      1) Atmospheric conditions
      2) Soil moisture conditions
      3) Vegetation phenological cycle characteristics
      4) Tidal stage

3. **Conduct image processing of remote sensor data to extract upland and wetland information**
   a. Acquire appropriate change detection data
      1) In situ and collateral data
      2) Remotely sensed data
         a) Base year (Time *b*)
         b) Subsequent year(s) (Time *b*–1 or *b*+1)
   b. Preprocess the multiple-date remotely sensed data
      1) Geometric rectification
      2) Radiometric correction (or normalization)
   c. Select appropriate change detection algorithm from the three C-CAP alternatives
   d. Apply appropriate image classification logic if necessary
      1) Supervised
      2) Unsupervised
      3) Hybrid
   e. Perform change detection using GIS algorithms
      1) Highlight selected classes using change detection matrix
      2) Generate change map products
      3) Compute change statistics

4. **Conduct quality assurance and control**
   a. Assess spatial data quality
   b. Assess statistical accuracy of
      1) Individual date classification
      2) Change detection products

5. **Distribute C-CAP Results**
   a. Digital products
   b. Analog (hardcopy) products

Chapter 2
The C-CAP Coastal Land-Cover Classification System

Introduction

It is essential that the coastal land-cover information stored in the C-CAP database be taxonomically correct and consistent with coastal wetland information derived from other agencies. The C-CAP Coastal Land-Cover Classification System (Table 2) includes three Level I superclasses (Klemas et al., 1993):

1.0-Upland,
2.0-Wetland, and
3.0-Water and Submerged Land.

These superclasses are subdivided into classes and subclasses at Levels II and III, respectively. While the categories Wetland and Water and Submerged Land constitute the primary habitats of interest to NOAA, Uplands are also included because they influence adjacent wetlands and water bodies. The classification system is hierarchical, reflects ecological relationships, and focuses on land-cover classes that can be discriminated primarily from satellite remote sensor data. It was adapted and designed to be compatible with other nationally standardized classification systems, especially

- the U.S. Geological Survey (USGS) "Land Use and Land Cover Classification System For Use with Remote Sensor Data" (Anderson et al., 1976; USGS, 1992; Appendix Table 1),
- the U.S. Fish and Wildlife Service (USFWS) "Classification of Wetlands and Deepwater Habitats of the United States" (Cowardin et al., 1979; Wilen, 1990; Appendix Table 2), and
- the U.S. Environmental Protection Agency (USEPA) Environmental Monitoring and Assessment Program (EMAP) classification system.

Dedicated workshops on the C-CAP classification system and productive discussions and reviews with representatives from each of these major agencies resulted in a classification system that is in harmony with other major U.S. land-cover databases. The C-CAP Coastal Land-Cover Classification System includes upland, wetland, submerged land, and water in a single, comprehensive scheme. An attempt has been made to identify land-cover classes that can be derived primarily through remote sensing and that are important indicators of ecosystem change. Modifications were necessary to reconcile inconsistencies between Anderson et al. (1976) and Cowardin et al. (1979) and to remove all land-use categories (Dobson, 1993a). C-CAP focuses on land cover and its relationship to other functional components of landscape (Dobson, 1993b). Definitions of the pertinent terms are as follows:

- land cover—vegetation, soils, rocks, water (in its various forms), and constructed materials covering the land surface, physically present and visible.
- land use—economic and cultural activities, permitted or not, that are practiced at a place which may or may not be manifested as visible land-cover features. For example, forestry land use may be visibly manifested as forest land cover, but recreational land use may occur in many different types of land cover, often without visible evidence of recreational use.
- landscape—the zone of interaction and convergence of the atmosphere, the hydrosphere, and the solid earth. Its vertical bounds are determined by the frequency and extent of interactions pertinent to a given field of inquiry. Horizontally, landscape may be divided into areal units defined by physical or cultural features pertinent to a field of inquiry.

While all categories of the C-CAP classification system can be represented as two-dimensional features at the mapping scale of 1:24,000, some features may be mapped as lines (e.g. a Marine/Estuarine Rocky Shore) or points (e.g. unique landmarks). Most linear and point features will be obtained from nonsatellite sources of information (e.g. aerial photography or in situ measurement using GPS). Those classes and subclasses that are required by C-CAP and which each regional C-CAP project will include in its database are underlined in Table 2. The underlined classes, with the exception of aquatic beds, can generally be detected by satellite remote sensors, particularly when supported by surface in situ measurement.

Superclasses of the C-CAP System

Uplands

The Upland superclass consists of seven subclasses (Table 2): Developed Land, Cultivated Land, Grassland, Woody Land, Bare Land, Tundra, and Snow/Ice. Upland classes are adapted from Level I classes in the USGS Land-Use and Land-Cover Classification System (Anderson et al., 1976; USGS, 1992; Appendix Table 1). Detailed definitions of all C-CAP classes and subclasses in Table 1 are found in Appendix 3.

Table 2

C-CAP Coastal Land-Cover Classification System (Modified from Klemas et al., 1993). C-CAP is committed to include the underlined classes in the land cover change databases.

1.0 Upland

- 1.1 <u>Developed Land</u>
  - 1.11 High Intensity
  - 1.12 Low Intensity
- 1.2 <u>Cultivated Land</u>
  - 1.21 Orchards/Groves/Nurseries
  - 1.22 Vines/Bushes
  - 1.23 Cropland
- 1.3 <u>Grassland</u>
  - 1.31 Unmanaged
  - 1.32 Managed
- 1.4 <u>Woody Land</u>
  - 1.41 Deciduous
    - 1.411 Forest
    - 1.412 Scrub/Shrub
  - 1.42 Evergreen
    - 1.421 Forest
    - 1.422 Scrub/Shrub
  - 1.43 Mixed
    - 1.431 Forest
    - 1.432 Scrub/Shrub
- 1.5 <u>Bare Land</u>
- 1.6 Tundra
- 1.7 Snow/Ice
  - 1.71 Perennial Snow/Ice
  - 1.72 Glaciers

2.0 Wetland

- 2.1 Marine/Estuarine Rocky Shore
  - 2.11 Bedrock
  - 2.12 Rubble
- 2.2 Marine/Estuarine Unconsolidated Shore (Beach, Flat, Bar)
  - 2.21 Cobble-gravel
  - 2.22 Sand
  - 2.23 Mud/Organic
- 2.3 <u>Marine/Estuarine Emergent Wetland</u>
  - 2.31 Haline (Salt Marsh)
  - 2.32 Mixohaline (Brackish Marsh)
- 2.4 <u>Estuarine Woody Wetland</u>
  - 2.41 Deciduous
    - 2.411 Forest
    - 2.412 Scrub/shrub
    - 2.413 Dead
  - 2.42 Evergreen
    - 2.421 Forest
    - 2.422 Scrub/Shrub
    - 2.423 Dead
  - 2.43 Mixed
    - 2.431 Forest
    - 2.432 Scrub/shrub
    - 2/433 Dead
- 2.5 Riverine Unconsolidated Shore (Beach, Flat, Bar)
  - 2.51 Cobble-Gravel
  - 2.52 Sand
  - 2.53 Mud/Organic
- 2.6 Lacustrine Unconsolidated Shore (Beach, Flat, Bar)
  - 2.61 Cobble-Gravel
  - 2.62 Sand
  - 2.63 Mud/Organic
- 2.7 Palustrine Unconsolidated Shore (Beach, Flat, Bar)
  - 2.71 Cobble-Gravel
  - 2.72 Sand
  - 2.73 Mud/Organic
- 2.8 <u>Palustrine Emergent Wetland</u> (Persistent)
- 2.9 <u>Palustrine Woody Wetland</u>
  - 2.91 Deciduous
    - 2.911 Forest
    - 2.912 Scrub/shrub
    - 2.913 Dead
  - 2.92 Evergreen
    - 2.921 Forest
    - 2.922 Scrub/shrub
    - 2.923 Dead
  - 2.93 Mixed
    - 2.931 Forest
    - 2.932 Scrub/shrub
    - 2.933 Dead

3.0 Water and Submerged Land

- 3.1 <u>Water</u>
  - 3.11 Marine/Estuarine
  - 3.12 Riverine
  - 3.13 Lacustrine (Basin > 20 acres)
  - 3.14 Palustrine (Basin < 20 acres)

Table 2 (continued)

3.2 Marine/Estuarine Reef

3.3 Marine/Estuarine Aquatic Bed

- 3.31 Algal (e.g., kelp)
- 3.32 Rooted Vascular (e.g., seagrass)
  - 3.321 (High Salinity (≥5 ppt; Mesohaline, Polyhaline, Euhaline, Hyperhaline)
  - 3.322 Low Salinity (< 5 ppt; Oligohaline, Fresh)

3.4 Riverine Aquatic Bed

- 3.41 Rooted Vascular/Algal/Aquatic Moss
- 3.42 Floating Vascular

3.5 Lacustrine Aquatic Bed (Basin > 20 acres)

- 3.51 Rooted Vascular/Algal/Aquatic Moss
- 3.52 Floating Vascular

3.6 Palustrine Aquatic Bed (Basin < 20 acres)

- 3.61 Rooted Vascular/Algal/Aquatic Moss
- 3.62 Floating Vascular

Developed Land (derived from the Anderson et al. [1976] Urban or Built-Up class) characterizes constructed surfaces composed of concrete, asphalt, roofing, and other building materials with or without vegetation. This class has been divided into two subclasses based on the amount of constructed surface relative to the amount of vegetated surface present. High-Intensity Developed Land contains little or no vegetation. This subclass includes heavily built-up urban centers as well as large constructed surfaces in suburban and rural areas. Large buildings (such as multiple-family housing, hangars, and large barns), interstate highways, and runways typically fall into this subclass. Low-Intensity Developed Land contains substantial amounts of constructed surface mixed with substantial amounts of vegetated surface. Small buildings (such as single family housing, farm outbuildings, and sheds), streets, roads, and cemeteries with associated grasses and trees typically fall into this subclass.

Cultivated Land ("Agricultural Land" of Anderson et al. [1976]) includes herbaceous (cropland) and woody (orchards, nurseries, vineyards, etc.) cultivated lands. Seasonal spectral signatures, geometric field patterns, and road network patterns may help identify this land-cover type. Always associated with agricultural land use, cultivated land is used for the production of food and fiber.

Grassland differs from "Rangeland" of Anderson et al. (1976) by excluding shrub-brushlands. Unmanaged Grasslands are dominated by naturally occurring grasses and forbs which are not fertilized, cut, tilled, or planted regularly. Managed Grasslands are maintained by human activity such as fertilization and irrigation, are distinguished by enhanced biomass productivity, and can be recognized through vegetative indices based on spectral characteristics. Examples of such areas include lawns, golf courses, forest or shrub areas converted to grassland, or areas of permanent grassland with altered species composition. This category includes managed pastures and pastures with vegetation that grows vigorously as fallow. Managed Grasslands are used for grazing or for growing and harvesting hay and straw for animal feed.

Woody Land includes nonagricultural trees and shrubs. The category alleviates the problem of separating various sizes of trees and shrubs using satellite remote sensor data but allows a height-based separation if high resolution aerial photographs are available. The class may be partitioned into three subclasses: Deciduous, Evergreen, and Mixed. These three subclasses generally can be discriminated with satellite remote-sensing systems.

Bare Land (derived from Barren Land of Anderson et al. [1976]) is composed of bare soil, rock, sand, silt, gravel, or other earthen material with little or no vegetation. Anderson et al.'s Barren Land was defined as having limited ability to support life; C-CAP's Bare Land is defined by the absence of vegetation without regard to inherent ability to support life. Vegetation, if present, is more widely spaced and scrubby than that in the vegetated classes. Unusual conditions such as a heavy rainfall may occasionally result in growth of a short-lived, luxuriant plant cover. Wet, nonvegetated, exposed lands are included in the Wetland categories. Bare Land may be bare temporarily because of human activities. The transition from Woody Land, Grassland, or Cultivated Land to Developed Land, for example, usually involves a Bare Land phase. Developed Land also may have temporary waste and tailing piles. Woody Land may be clearcut, producing a temporary Bare Land phase. When it may be inferred from the data that the lack of vegetation is due to an annual cycle of cultivation (e.g. plowing), the land is not included in the Bare Land class. Land temporarily without vegetative cover because of cropping or tillage is classified as Cultivated Land, not Bare Land.

Wetlands

Wetlands are lands where saturation with water is the dominant factor determining soil development and the types of plant and animal communities living in the soil and on its surface (Cowardin et al., 1979). A characteristic feature shared by all wetlands is soil or substrate that is at least periodically saturated with or covered by water. The upland limit of wetlands is designated as 1) the boundary between land with predominantly hydrophytic cover and land with predominantly mesophytic or xerophytic cover; 2) the boundary between soil that is predominantly hydric and soil that is predominantly nonhydric; or 3) in the case of wetlands without vegetation or soil, the boundary between land that is flooded or saturated at some time during the growing season each year and land that is not (Cowardin et al., 1979). Most wetlands are vegetated and found on soil.

Wetland in the C-CAP Coastal Land-Cover Classification System (Table 2) includes all areas considered wetland by Cowardin et al. (1979) except for bottoms, reefs, aquatic beds, and nonpersistent emergent wetlands. The class subdivision was adopted primarily from the Cowardin et al. system, shown in Appendix Table 2. At Level II, C-CAP incorporates certain Cowardin et al. classes (e.g. Rocky Shore, Unconsolidated Shore, Emergent Wetland) or grouped Cowardin et al. classes (e.g. Woody Wetland may be further divided into Scrub-Shrub and Forested categories) in combination with Cowardin et al. systems (i.e. Marine, Estuarine, Riverine, Lacustrine, Palustrine). Thus, a typical Level II class in the C-CAP system might be Palustrine Woody Wetland.

Marine and Estuarine Rocky Shores (Cowardin et al., 1979) were combined into a single class, Marine/Estuarine Rocky Shore. The same logic was used to produce Marine/Estuarine Unconsolidated Shore.

Salinity exhibits a horizontal gradient in coastal estuarine marshes. This is evident not only through the direct measurement of salinity but in the horizontal distribution of marsh plants (Daiber, 1986). Therefore, the Estuarine Emergent Wetland class is partitioned into Haline (Salt) and Mixohaline (Brackish) Marshes. For both subclasses, the C-CAP classification system uses the Cowardin et al. (1979) definitions. Mixohaline salinity ranges from 0.5 ppt to 30 ppt, and Haline salinity is ≥30 ppt. Within a marsh, plant zonation is usually quite evident. Along the Atlantic coast of North America the pioneer plant on regularly flooded mudflats is saltmarsh cordgrass, *Spartina alterniflora*, which often appears in pure stands. In more elevated areas that are flooded less frequently, saltmeadow hay, *Spartina patens*, often dominates. The upland interfaces are bordered by marsh elder, *Iva frutescens*, and groundsel tree, *Baccharis halimifolia*. Thus, salt marshes may be subdivided further into High Marsh and Low Marsh, but this distinction is not required in C-CAP regional projects.

The C-CAP Coastal Land-Cover Classification System does not attempt to identify freshwater nonpersistent emergent wetlands because they are invisible during much of the year and are difficult to detect by remote sensors. These wetlands are classified as Riverine Water and Lacustrine Water.

Water and Submerged Land

All areas of open water with <30% cover of trees, shrubs, persistent emergent plants, emergent mosses, or lichens are assigned to the superclass Water and Submerged Land, whether the area is considered wetland or deepwater habitat under the Cowardin et al. (1979) classification.

The Water class includes Cowardin et al.'s (1979) classes Rock Bottom and Unconsolidated Bottom, and Nonpersistent Emergent Wetlands, as well as Reefs and Aquatic Beds that are not identified as such. Most C-CAP products will display water as a single class. However, the major systems (Marine/Estuarine, Riverine, Lacustrine, Palustrine) are ecologically different from one another, and for this reason, the C-CAP system identifies the four systems as Level III subclasses: 3.11-Marine/Estuarine Water, 3.12-Riverine Water, 3.13-Lacustrine Water, and 3.14-Palustrine Water. While C-CAP does not require these subclasses, the option is provided to participants who may have such data available from ancillary sources. Having the water subclasses also makes the C-CAP scheme more compatible with the Cowardin et al. (1979) system. The subclass 3.11-Marine/Estuarine Water includes Bottoms and undetected Reefs and Aquatic Beds. The subclasses 3.12-Riverine Water, 3.13-Lacustrine Water, and 3.14-Palustrine Water include Bottoms and undetected Aquatic Beds as well as Nonpersistent Emergent Wetlands. Palustrine waterbodies, defined as covering <20 acres, are smaller than Lacustrine waterbodies.

C-CAP combined Marine and Estuarine Reefs and Aquatic Beds into two classes: Marine/Estuarine Reefs and Marine/Estuarine Aquatic Beds. Marine/Estuarine Aquatic Beds includes the subclass Rooted Vascular, which is subdivided into High Salinity (≥5 ppt) and Low Salinity (<5 ppt). The ≥5 ppt salinity level separates seagrasses from submersed grasses and forbs that tolerate or require low salinity. Both types of plants define aquatic beds, submersed habitats that are important to the C-CAP project. High Salinity includes mesohaline, polyhaline, euhaline, and hyperhaline salinity categories of Cowardin et al. (1979). Low Salinity includes oligohaline and fresh categories (<5 ppt salinity).

With the noted exceptions, most of the Wetland and Water classes have definitions similar to those contained in Cowardin et al. (1979) so that data can be interchanged with other programs, such as the USFWS National Wetlands Inventory (NWI) program, which is based on the Cowardin et al. (1979) classification system. Detailed definitions of all superclasses, classes, and subclasses shown in Table 2 are provided in Appendix 3.

Chapter 3

Monitoring Uplands and Wetlands Using Satellite Remote Sensor Data

Successful remote-sensing change detection of uplands and wetlands in coastal regions requires careful attention to 1) sensor systems, 2) environmental characteristics, and 3) geodetic control. Failure to understand the impact of the various parameters on the change detection process can lead to inaccurate results. Ideally, the remotely sensed data used to perform C-CAP change detection are acquired by a remote sensor system that holds the following factors constant: temporal, spatial (and look angle), spectral, and radiometric. It is instructive to review each of these parameters and identify why they have a significant impact on the success of C-CAP remote-sensing change detection projects. Table 3 summarizes the characteristics of some of the most important satellite remote-sensing systems.

Remote-Sensing System Considerations

Temporal Resolution

Two important temporal resolutions should be held constant when performing coastal change detection using multiple dates of remotely sensed data. First, the data should be obtained from a sensor system which acquires data at approximately the same time of day (e.g. Landsat TM data are acquired before 0945 h for most of the conterminous United States). This eliminates diurnal sun angle effects which can cause anomalous differences in the reflectance properties of remotely sensed objects. Second, whenever possible it is desirable to use remotely sensed data acquired on anniversary dates (e.g. 1 October 1988 versus 1 October 1993). Using anniversary date imagery removes seasonal sun angle differences that can make change detection difficult and unreliable (Jensen et al., 1993a). Usually, precise anniversary date imagery is not available. The determination of acceptable near-anniversary dates then depends on local and regional factors such as phenological cycles and annual climatic regimes.

Spatial Resolution and Look Angle

Accurate spatial registration of at least two images is essential for digital change detection. Ideally, the remotely sensed data are acquired by a sensor system that collects data with the same instantaneous-field-of-view (IFOV) on each date. For example, Landsat TM data collected at 30 × 30 m spatial resolution (Table 3) on two dates are relatively easy to register to one another. Geometric rectification algorithms (Jensen, 1986; Novak, 1992) are used to register the images to a standard map projection (Universal Transverse Mercator [UTM] for most U.S. projects). Rectification should result in the two images having a root mean square error (RMSE) of $\leq \pm 0.5$ pixel. RMSE $\geq \pm 0.5$ pixel may result in the identification of spurious areas of change between the two datasets. See "Rectification of Multiple-date Remote Sensor Data" for a summary of C-CAP image rectification requirements.

It is possible to perform change detection using data collected by two different sensor systems with different IFOV's, e.g. Landsat TM data (30 x 30 m) for date 1 and SPOT HRV data (20 × 20 m) for date 2. In such cases, it is necessary to decide upon a representative minimum mapping unit (e.g. 20 × 20 m) and then resample both datasets to this uniform pixel size. This does not present a significant problem as long as one remembers that the information content of the resampled data can never be greater than the IFOV of the original sensor system (i.e. even though the Landsat TM data are resampled to 20 × 20 m pixels, the information was still acquired at 30 × 30 m resolution, and one should not expect to be able to extract additional spatial detail in the dataset).

Some remote-sensing systems like SPOT collect data at off-nadir look angles as much as ±20° (Table 3), i.e. the sensors obtain data of an area on the ground from an "oblique" vantage point. Two images with significantly different look angles can cause problems when used for change detection purposes. For example, consider a maple forest consisting of very large, randomly spaced trees. A SPOT image acquired at 0° off-nadir will look directly down upon the "top" of the canopy. Conversely, a SPOT image acquired at 20° off-nadir will record reflectance information from the "side" of the canopy. Differences in reflectance from the two datasets can cause spurious change detection results. Therefore, the data used in a remote-sensing digital change detection should be acquired with approximately the same look angle whenever possible.

Spectral Resolution

A fundamental assumption of digital change detection is that there should exist a difference in the spectral response of a pixel on two dates if the biophysical materials within the IFOV have changed between dates. Ideally, the spectral resolution of the remote sensor

Table 3

Selected satellite remote-sensing system characteristics; abbreviations: MSS=multispectral scanner; TM=thematic mapper.

Remote sensor system	Spectral resolution (μm)	Spatial resolution (m)	Temporal resolution (d)	Radiometric resolution (bits)
Landsat MSS 1–5	Band 1 (0.50–0.60)	80 × 80	18	8[1]
	Band 2 (0.60–0.70)	80 × 80	18	8
	Band 3 (0.70–0.80)	80 × 80	18	8
	Band 4 (0.80 –1.1)	80 × 80	18	8
Landsat TM 4–6	Band 1 (0.45–0.52)	30 × 30	16	8
	Band 2 (0.52–0.60)	30 × 30	16	8
	Band 3 (0.63–0.69)	30 × 30	16	8
	Band 4 (0.76–0.90)	30 × 30	16	8
	Band 5 (1.55–1.75)	30 × 30	16	8
	Band 7 (2.08–2.35)	30 × 30	16	8
	Band 6 (10.4–12.5)	120 × 120	16	8
Landsat TM 6, PAN[2]	Band 8 (0.5–0.90)	15 × 15	16	8
SPOT HRV, XS	Band 1 (0.50–0.59)	20 × 20	pointable	8
	Band 2 (0.61–0.68)	20 × 20	pointable	8
	Band 3 (0.79–0.89)	20 × 20	pointable	8
SPOT HRV, PAN	Pan (0.51–0.73)	10 × 10	pointable	8

[1] Landsat MSS 1 and 2 collected data in 7 bits.

[2] The panchromatic (PAN) band was found on Landsat 6, which was lost during a launch mishap.

system is sufficient to record reflected radiant flux in spectral regions that best capture the most descriptive spectral attributes of the object. Unfortunately, different sensor systems do not record energy in exactly the same portions of the electromagnetic spectrum, i.e. bandwidths (Table 3). For example, Landsat MSS records energy in four relatively broad bands, SPOT HRV sensors record in three relatively coarse multispectral bands and one panchromatic band, and TM records in six relatively narrow optical bands and one broad thermal band (Table 3). Ideally, the same sensor system is used to acquire imagery on multiple dates. When this is not possible, the analyst should select bands which approximate one another. For example, SPOT bands 1 (green), 2 (red), and 3 (near-infrared) can be used successfully with TM bands 2 (green), 3 (red), and 4 (near-infrared) or MSS bands 1 (green), 2 (red), and 4 (near-infrared). Many of the change detection algorithms to be discussed do not function well when bands from one sensor system do not match those of another sensor system. For example, using TM band 1 (blue) with either SPOT or MSS data is not wise.

Radiometric Resolution

Converting satellite remote sensor data from analog to digital usually results in 8-bit brightness values with values ranging from 0 to 255 (Table 3). Ideally, the sensor systems collect the data at the same radiometric precision on both dates. When the radiometric resolution of data acquired by one system (e.g. MSS 1 with 7-bit data) are compared with data acquired by a higher radiometric resolution instrument (e.g. TM with 8-bit data) then the lower resolution data (e.g. 7-bit) should be "decompressed" to 8-bit data for change detection purposes. However, the precision of decompressed brightness values can never be better than the original, uncompressed data.

The Preferred C-CAP Satellite Sensor System

TM is currently the primary sensor recommended for C-CAP image acquisition and change analysis for all land cover except aquatic beds. Although its spatial resolution is not as good as that of a SPOT satellite or aircraft MSS image, a TM image is generally less expensive to acquire and process for large-area coverage. Compared with SPOT imagery, TM has better spectral resolution and specific spectral bands that are more applicable to wetlands delineation (bands 5 and 7). In addition, TM is preferred over SPOT because TM has collected data for a longer time (since 1982, as opposed to SPOT since 1986) and because many TM scenes of U.S. coastal regions were systematically collected on a routine basis.

There are advantages and disadvantages to using other sensors. Aircraft multispectral scanners are more expensive and complex to use over large regions (Jensen et al., 1987). However, good algorithms are now available for georeferencing, and in certain cases (e.g. when higher spectral or spatial resolution is needed and when unfavorable climatic conditions for satellite sensors exist) aircraft sensors may be optimum. The SPOT sensor has a greater temporal coverage because the satellite can collect data off-nadir. However, if off-nadir SPOT imagery is used for C-CAP change analyses, the data must be normalized to compensate for different look angles that may preclude pixel-to-pixel spectral-change analysis. Nevertheless, SPOT imagery may be a reasonable alternative in certain areas because of cloud cover or other impediments to TM data availability.

C-CAP remains flexible to take advantage of new sensors and other technologies that become operational during the lifetime of the program. Regional participants should work with the C-CAP program coordinators to ensure that the sensor selection meets the following C-CAP requirements:

- Standard radiometrically corrected TM data are required, and geocoded (georeferenced) data are optional. If geocoded data are selected, the coordinate system should be UTM.
- Regional participants must collaborate with C-CAP managers to ensure that the exchange medium and its format will be amenable to the processing capabilities of the participants.
- C-CAP normally will purchase and archive the raw data in collaboration with the regional image processing center. In cases where the regional participants already have usable raw imagery or are making their own purchases, formal agreements between C-CAP managers and participants must address vendor licensing and other legal requirements as well as C-CAP archiving and quality-control protocol.

Important Environmental Characteristics

Failure to understand the impact of various environmental characteristics on the remote-sensing change detection process can also lead to inaccurate C-CAP results. When performing change detection it is desirable to hold environmental variables as constant as possible. Specific environmental variables and their potential impacts are described below.

Atmospheric Conditions

There should be no clouds, haze, or extreme humidity on the days remote-sensing data are collected. Even a thin layer of haze can alter spectral signatures in satellite images enough to create the false impression of spectral change between two dates. Obviously, 0% cloud cover is preferred for satellite imagery and aerial photography. At the upper limit, cloud cover >20% is usually unacceptable. In addition, clouds not only obscure terrain but the cloud shadow also causes major image classification problems. Any area obscured by clouds or affected by cloud shadow will filter through the entire change detection process, severely limiting the utility of the final change detection product. Therefore, regional analysts must use good professional judgment to evaluate such factors as the criticality of the specific locations affected by cloud cover and shadow and the availability of timely surrogate data for those areas obscured (e.g. perhaps substituting aerial photography interpretation for a critical area). Even when the stated cloud cover is 0%, it is advisable to "browse" the proposed image on microfiche at the National Cartographic Information Center in each State to confirm that the cloud cover estimate is correct.

Assuming no cloud cover, the use of anniversary dates helps to ensure general, seasonal agreement between the atmospheric conditions on the two dates. However, if dramatic differences exist in the atmospheric conditions present on the *n* dates of imagery to be used in the change detection process, it may be necessary to remove the atmospheric attenuation in the imagery. Two alternatives are available. First, sophisticated atmospheric transmission models can be used to correct the remote-sensor data if substantial in situ data are available on the day of the overflights. Second, an alternative empirical method may be used to remove atmospheric effects. A detailed description of one empirical method of image-to-image normalization is found in "Radiometric Normalization of Multiple-Date Images.

Soil Moisture Conditions

Ideally, the soil moisture conditions should be identical for the *n* dates of imagery used in a change detection project. Extremely wet or dry conditions on one date can cause serious change detection problems. Therefore, when selecting the remotely sensed data to be used for change detection it is very important not only to look for anniversary dates but also to review precipitation records to determine how much rain or snow fell in the days and weeks prior to data collection. When soil moisture differences between dates are significant for only certain parts of the study area (perhaps due to a local thunderstorm), it may be necessary to stratify (eliminate) those affected areas and perform a separate analysis that can be added back in the final stages of the project.

Vegetation Phenological Cycle Characteristics

Vegetation grows according to seasonal and annual phenological cycles. Obtaining near-anniversary images greatly minimizes the effects of wetland seasonal phenological differences that may cause spurious change to be detected in the imagery. One must also be careful about two other factors when dealing with upland seasonal agricultural crops. First, many monoculture crops (e.g. corn) normally are planted at approximately the same time of year. A month lag in planting date between fields having the same crop can cause serious change detection error. Second, many monoculture crops are composed of different species (or strains) of the same crop, which can cause the crop to reflect energy differently on multiple dates of anniversary imagery. These observations suggest that the analyst must know the biophysical characteristics of the vegetation as well as the cultural land-tenure practices in the study area so that imagery which meets most of these characteristics can be selected for change detection.

The choice of image date is best determined by mutual agreement among remote-sensing specialists, biologists, ecologists, and local experts. The selection of the acceptable window of acquisition will be made independently by participants in each region. No single season will serve for all areas because of substantial latitudinal variation extending from temperate to tropical regions. For example, coastal marshes in the mid-Atlantic region are best inventoried from June through October while submersed habitats in southern Florida may be best inventoried in November. Even within regions, some cover types will be more easily distinguished in different seasons. For example, in the Caribbean, estuarine seagrasses can be best detected in early January, yet marine seagrasses can be best detected in May or June. Technically, these vegetation patterns should be monitored at optimal times throughout the year, but cost limitations usually limit the analyst to a single date.

Effects of Tidal Stage on Image Classification

Tidal stage is a crucial factor in satellite image scene selection and the timing of aerial surveys. Ideally, tides should be constant between time periods, but this would rule out synoptic satellite sensors since tidal stages are not synchronized within a region or even within a single image. Alternatively, analysts should avoid selecting the highest tides and should take into account the tide stages occurring throughout each scene. Tidal effect varies greatly among regions. In the Northwest, for example, when all of the temporal, atmospheric, and tidal criteria are taken into account, the number of acceptable scenes may be quite small. In some regions it may be necessary to seek alternative data such as SPOT satellite data, aerial photographs, or other land-cover databases. For most regions, mean low tide (MLT) or lower will be preferred, one or two feet above MLT will be acceptable, and three feet or more will be unacceptable (Jensen et al., 1993a). Ideally, tides for aerial photographic surveys of submersed habitat should approach low tide as predicted in NOS tide tables, but optimal visualization of the subtidal bottom depends on water clarity as well as depth. Two of the 1993 C-CAP protocol development projects focus on improving the C-CAP protocol for tidal effects (see Appendix 5).

Image Processing Data to Inventory Upland and Wetland Change

With the classification scheme developed and the appropriate remote-sensor data selected, it is possible to process the data to extract upland and wetland change information. This involves geometric and radiometric correction, selection of an appropriate change detection algorithm, classification if necessary, creation of change detection products, and error evaluation (Table 1). A separate section (Chapter 4) describes the extraction of information on SRV because aerial photography and significantly different photogrammetric techniques must be utilized.

Rectification of Multiple-Date Remote Sensor Data

Georeferencing (spatial registration of a remotely sensed image to a standard map projection) is a necessary step in digital change detection and cartographic representation. The following C-CAP recommendations should be followed when rectifying the base image to a standard basemap:

- Geocoded base TM images can be purchased if preferred by regional analysts. However, participants should be aware that some analysts have reported undocumented variations in commercial products that can lead to poor registration in certain regions, especially where local relief requires substantial terrain correction. Additional registration may be necessary to achieve the C-CAP standard precision of RMSE ±0.5 pixel. Therefore, it is recommended that each regional project perform its own base image-to-map rectification by using data that is radiometrically corrected but not geocoded.
- Ground control points (GCP's) used to compute rectification transformation coefficients should be rela-

tively static features in the landscape (e.g. road intersections) or should be based on new GPS measurements taken in the field. When GCP's are digitized from USGS 7.5' (1:24,000) maps, analysts should use the marginal information and available updates to improve the location of control points. GCP's should be extracted from mylar copies of the USGS maps whenever possible to minimize system-produced digitizing error. Traditional paper maps expand and contract with changes in relative humidity and should not be used for digitizing GCP's.

- C-CAP recommends the use of the current NAD '83 national datum. Unfortunately, most existing map series are based on the NAD '27 datum. NAD '27 will be acceptable on a region-by-region basis until published maps based on NAD '83 are universally available.
- In all but the flattest coastal regions, terrain correction of imagery may be necessary to reduce image distortion caused by local relief.
- The required coordinate system is UTM. If another coordinate system is used (e.g. state plane), it is the responsibility of the regional analyst to provide complete documentation and conversion equations.
- It is the responsibility of the regional analyst to understand (or seek advice concerning) the variety of rectification-resampling algorithms (e.g. bilinear interpolation, nearest neighbor, cubic convolution) and their impact on the data. Nearest-neighbor resampling is recommended.

Rectification of an earlier date (T_{b-1}) or later date (T_{b+1}) to the base image (T_b) can be accomplished in several ways. The primary concern is to accomplish the most exact co-registration of pixels from each time period and thus reduce a potentially significant source of error in change analysis (Lunetta et al., 1991). The following are minimum recommendations and requirements:

- Geocoded and terrain-corrected TM data can be ordered from commercial vendors. Two separate images can be overlaid according to like coordinates, but this technique may introduce error if prior geocoding was not precisely the same in both images. The regional analyst has no control in this process, but if high precision is accomplished by the vendor, the analyst can significantly reduce image processing effort at the regional facility.
- The regional analyst can geocode the image to UTM coordinates as was done with the base image. If this technique is adopted, it is important to use the identical GCP's and resampling algorithm that were used to rectify the base image.
- For multiple images, the preferred technique is to rectify nongeocoded images directly to the geocoded base image. This technique may have the advantage of reducing or better controlling co-registration error among images. Selection and consistency of control points and rectification algorithms are important to the success of this technique. Cubic convolution algorithms normally yield the most precise spatial fit, but cubic convolution and bilinear interpolation algorithms suffer from the disadvantage of averaging pixel brightness values. Nearest-neighbor algorithms are spatially less precise, but they offer the advantage of retaining pixel brightness values through the processes of rectification and registration.

Radiometric Normalization of Multiple-Date Images

The use of remotely sensed data to classify coastal and upland land cover on individual dates is contingent upon there being a robust relationship between remotely sensing brightness values (BV's) and actual surface conditions. However, factors such as sun angle, Earth/Sun distance, detector calibration differences between the various sensor systems, atmospheric condition, and sun/target/sensor geometry (phase angle) will also affect pixel brightness value. Differences in direct beam solar radiation due to variation in sun angle and Earth/sun distance can be calculated accurately, as can variation in pixel BV's due to detector calibration differences between sensor systems. Removing atmospheric and phase-angle effects requires information about the gaseous and aerosol composition of the atmosphere and the bidirectional reflectance characteristics of elements within the scene. However, atmospheric and bidirectional reflectance information are rarely available for historical remotely sensed data. Also, some analysts may not have the necessary expertise to perform a theoretically based atmospheric path radiance correction on remotely sensed data. Hence, it is suggested that a relatively straightforward "empirical scene normalization" be employed to match the detector calibration, astronomic, atmospheric, and phase-angle conditions present in a reference scene.

Image normalization reduces pixel BV variation caused by nonsurface factors, so variations in pixel BV's between dates can be related to actual changes in surface conditions. Normalization enables the use of image analysis logic developed for a base-year scene to be applied to other scenes. This can be accomplished using techniques pioneered by the U.S. Bureau of Land Management (Eckhardt et al., 1990). Image normalization is achieved by developing simple regression equations between the brightness values of "normalization targets" present in T_b and the scene to be normalized (e.g. T_{b-1} or T_{b+1}). Normalization targets are assumed to be constant reflectors, therefore any changes in their brightness values are attributed to detector calibration, astronomic, atmospheric, and phase-angle differences. Once these variations are removed, changes in BV may be related to changes in surface conditions.

Acceptance criteria for potential "normalization targets" (Eckhardt et al., 1990) are as follows:

- Targets must be at approximately the same elevation as the land cover of primary interest within the scene. Most aerosols in the atmosphere occur <1000 m above ground level (AGL). Selecting a mountain-top normalization target, thus, would be of little use in estimating atmospheric conditions near sea level. Although C-CAP projects are on the coast, many regions include areas of substantial local relief.
- Targets should contain only minimal amounts of vegetation. Vegetation spectral reflectance can change over time because of environmental stresses and plant phenology. Good targets include bare soil fields and deep, nonturbid water bodies.
- Targets must be on relatively flat terrain so that incremental changes in sun angle between dates will have the same proportional increase or decrease in direct beam sunlight for all normalization targets.
- Normalization targets should have approximately the same texture over time. Changing textural patterns indicate variability within the target, which could mean that the reflectance of the target as a whole may not be constant over time. For example, a mottled pattern on what had previously been a uniformly gray, dry lake bed indicates changing surface moisture conditions, which would eliminate the dry lake bed from consideration as a normalization target.

The mean BV's of the T_b targets are regressed against the mean BV's of the T_{b-1} or T_{b+1} targets for the n bands used in the classification of the remote sensor data (e.g. TM bands 2, 3, and 4). The slope and y-intercept of the n equations are then used to normalize the T_{b+1} or T_{b-1} Landsat TM data to the T_b Landsat TM data. Each regression model contains an additive component (y-intercept) that corrects for the difference in atmospheric path radiance between dates and contains a multiplicative term (slope) that corrects for the difference in detector calibration, sun angle, Earth/Sun distance, atmospheric attenuation, and phase angle between dates.

It is customary first to normalize the remote-sensor data and then perform image rectification (using nearest-neighbor resampling if image classification is to take place). These data are then ready for individual date classification or the application of various multi-image change detection algorithms. Most studies that attempt to monitor biophysical properties such as vegetation biomass, chlorophyll absorption, and health require atmospheric correction.

Selecting the Appropriate Change Detection Algorithm

C-CAP is the first Federal program to state as a primary goal the monitoring of coastal habitat change using satellite technology (Cross and Thomas, 1992). The implementation and continuing evolution of the program is based on the fact that improved cartographic, digital image processing, and photointerpretation methods must be developed for a program of this geographic coverage, spatial resolution, and temporal frequency (nationwide, 30 × 30 m pixel, every one to five years). Initial implementation of C-CAP will require a blend of traditional and innovative approaches to change analysis. Because the program has adopted a digital format, with TM as a primary sensor, new techniques in processing can be easily incorporated into future iterations.

The selection of an appropriate change detection algorithm is very important (Jensen, 1986; Dobson and Bright, 1991, 1992, and 1993; Jensen et al., 1993a). First, it will have a direct impact on the type of image classification to be performed (if any). Second, it will dictate whether important "from-to" information can be extracted from the imagery. C-CAP requires that from-to information be readily available in digital form suitable for geographic analysis and for producing maps and tabular summaries. At least seven change detection algorithms are commonly used by the remote-sensing community:

1. Change Detection Using Write Function Memory Insertion—Example: Kittredge and Fort Moultrie, S.C.
2. Multiple-Date Composite Image Change Detection—No example provided.
3. Image Algebra Change Detection (Band Differencing or Band Ratioing)—No example provided.
4. Postclassification Comparison Change Detection—Example: Fort Moultrie, S.C.
5. Multiple-Date Change Detection Using a Binary Mask Applied to T_{b-1}—Example: Chesapeake Bay, Md.
6. Multiple-Date Change Detection Using Ancillary Data Source as T_b—No example provided.
7. Manual On-Screen Digitization of Change—No example provided.

It is instructive to review these alternatives, identify those acceptable to C-CAP, and provide specific examples where appropriate.

Change Detection Using Write Function Memory Insertion

It is possible to insert individual bands of remotely sensed data into specific write function memory banks (red, green, and/or blue) in the digital image processing system (Fig. 1) to visually identify change in the imagery (Jensen et al., 1993b). For example, consider two Landsat TM scenes of the Fort Moultrie quadrangle near Charleston, SC, obtained on 11 November 1982 and 19 December 1988. Band 1 of the 1982 image was placed in the green image plane; band 1 of the 1988 image, in the red image plane; and no image, in the blue image plane (Fig. 2). All areas that did not change between the two dates are depicted in shades of yellow (i.e. in additive color theory, equal intensities of green and red make yellow). The graphic depicts numerous changes, including

- beach and sand bar accretion (red) and erosion (green),
- new urban development (red), and
- changes in tidal stage between dates (green and red).

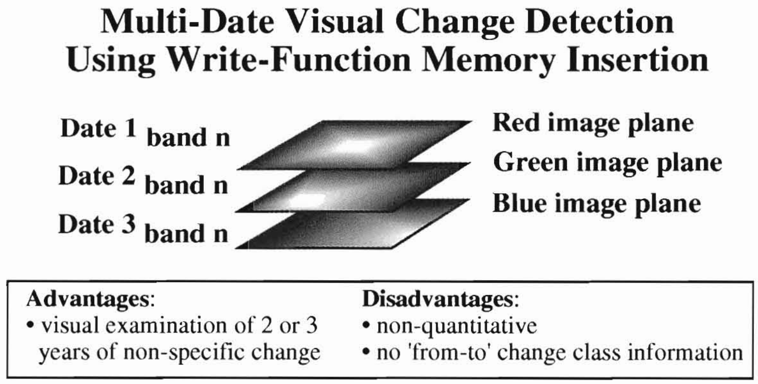


Figure 1
Diagram of Multiple-Date Change Detection using Write Function Memory insertion (Jensen, 1994).

Advantages of this technique include the possibility of looking at two and even three dates of remotely sensed imagery at one time, as demonstrated by Jensen et al. (1993b). Unfortunately, the technique does not produce a classified land-cover database for either date and, thus, does not provide quantitative information on the amount of area changing from one land-cover category to another. Nevertheless, it is an excellent analog method for quickly and qualitatively assessing the amount of change in a region, which might help to select one of the more rigorous change detection techniques to be discussed.

Multiple-Date Composite Image Change Detection

Numerous researchers have rectified multiple dates of remotely sensed imagery (e.g. selected bands of two TM scenes of the same region) and placed them in a single dataset (Fig. 3). This composite dataset can be analyzed in a number of ways to extract change information. First, a traditional classification using all n bands (six in the example in Fig. 3) may be performed. Unsupervised classification techniques will result in the creation of "change" and "no-change" clusters. The analyst must then label the clusters accordingly.

Other researchers have used principle component analysis (PCA) to detect change (Jensen, 1986). Again, the method involves registering two (or more) dates of remotely sensed data to the same planimetric basemap as described earlier and then placing them in the same dataset. A PCA based on variance–covariance matrices or a standardized PCA based on an analysis of correlation matrices is then performed (Fung and LeDrew, 1987 and 1988; Eastman and Fulk, 1993). This results in the computation of eigenvalues and factor loadings that are used to produce a new, uncorrelated PCA image dataset. Usually, several of the new bands of information are directly related to change. The difficulty arises when trying to interpret and label each component image. Nevertheless, the method is valuable and is used frequently.

The advantage of the techniques is that only a single classification is required. Unfortunately, it is often difficult to label the change classes, and no from-to change class information is available.

Image Algebra Change Detection

It is possible to simply identify the amount of change between two images by band ratioing or image differencing the same band in two images that have previously been rectified to a common basemap. Image differencing involves subtracting the imagery of one date from that of another (Fig. 4). The subtraction results in positive and negative values in areas of radiance change and zero values in areas of no-change in a new "change image." In an 8-bit (2^8) analysis with pixel values ranging from 0 to 255, the potential range of difference values is –255 to 255. The results are normally transformed into positive values by adding a constant, c (usually 255). The operation is expressed mathematically as

$$D_{ijk} = BV_{ijk}(1) - BV_{ijk}(2) + c$$

where
D_{ijk} = change pixel value,
$BV_{ijk}(1)$ = brightness value at T_b,
$BV_{ijk}(2)$ = brightness value at T_{b-1} or T_{b+1},

c = a constant (e.g. 255),
i = line number,
j = column number, and
k = a single band (e.g. TM band 4).

The "change image" produced using image differencing usually yields a BV distribution approximately Gaussian in nature, where pixels of no BV change are distributed around the mean and pixels of change are found in the tails of the distribution. Band ratioing involves exactly the same logic except a ratio is computed between T_b and T_{b+1} or T_{b-1} and the pixels that did not change have a value of "1" in the change image.

A critical element of both image-differencing and band-ratioing change detection is deciding where to place the threshold boundaries between "change" and

Figure 2

Example of Multiple-Date Change Detection using Write Function Memory Insertion using two dates of Landsat Thematic Mapper imagery of Fort Moultrie, S. C. Red image plane = TM band 3, 19 Dec 1988; green image plane = TM band 3, 9 Nov 1982; blue image plane = blank.

"no-change" pixels displayed in the histogram of the change image (Jensen, 1986). Often, a standard deviation from the mean is selected and tested empirically. Conversely, most analysts prefer to experiment empirically, placing the threshold at various locations in the tails of the distribution until a realistic amount of change is encountered. Thus, the amount of change selected and eventually "recoded" for display is often subjective and must be based on familiarity with the study area. There are also analytical methods that can be used to select the most appropriate thresholds. Unfortunately, image differencing simply identifies those areas that may have changed and provides no information on the nature of the change, i.e. no from-to information. Nevertheless, the technique is valuable when used in conjunction with other techniques such as the multiple-date change detection using a binary change mask to be discussed in "Multiple-Date Change Detection Using a Binary Change Mask Applied to T_{b-1} or T_{b+1}."

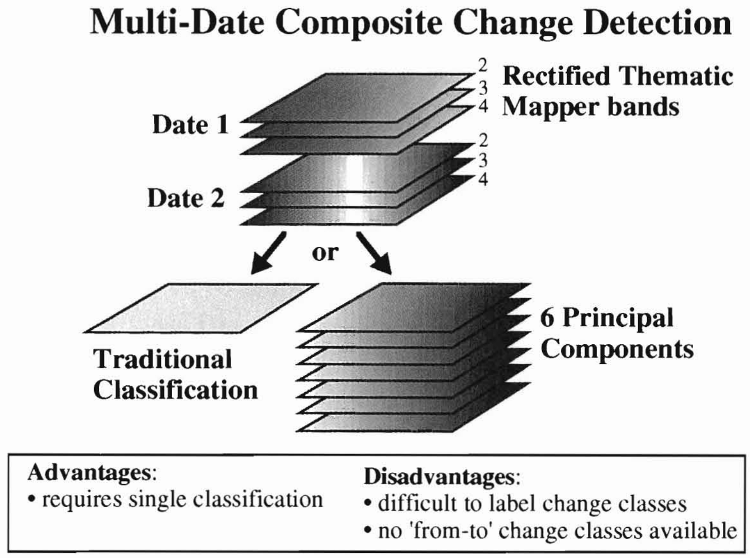


Figure 3
Diagram of Multiple-Date Composite Image Change Detection (Jensen, 1994).

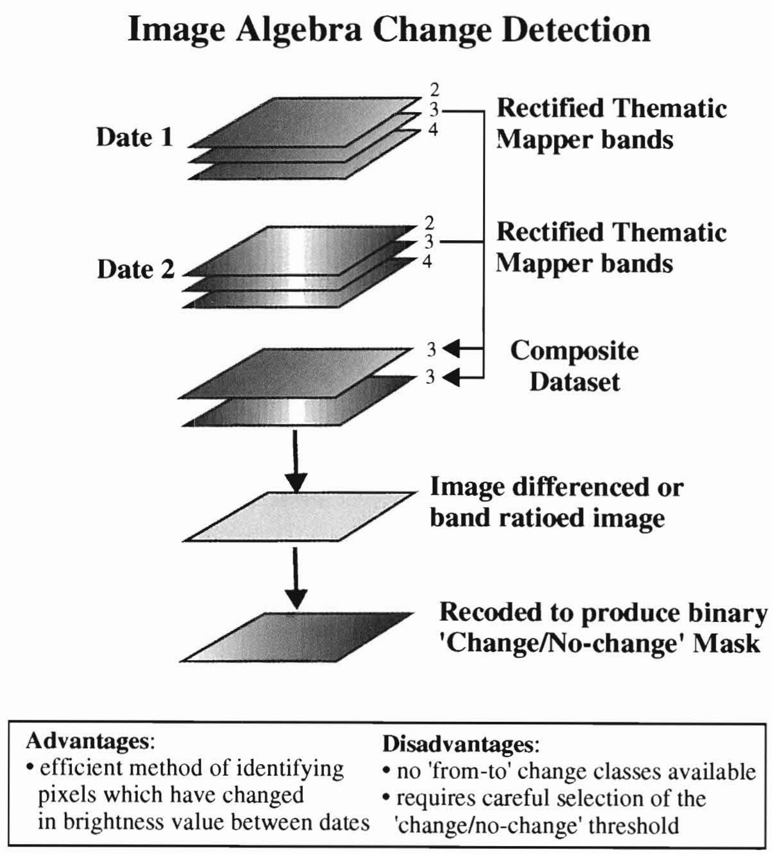


Figure 4
Diagram of Image Algebra Change Detection (Jensen, 1994).

Postclassification Comparison Change Detection

The most commonly used quantitative method of change detection is postclassification comparison (Jensen, 1986; Jensen et al., 1993a) and may be used in regional C-CAP projects under certain conditions. It requires rectification and classification of each of the remotely sensed images (Fig. 5). These two maps are then compared on a pixel-by-pixel basis by using a "change detection matrix" to be discussed. Unfortunately, every error in the individual date classification map will also be present in the final change detection map (Rutchey and Velcheck, 1993). Therefore, it is imperative that the individual classification maps used in the postclassification change detection method be extremely accurate (Augenstein et al., 1991; Price et al., 1992).

To demonstrate the postclassification comparison change detection method, consider the Kittredge (40 river miles inland from Charleston, S.C.) and Fort Moultrie, S.C. study areas (Fig. 6) (Jensen et al., 1993a). Nine classes of land cover were inventoried on each date (Fig. 7). The 1982 and 1988 classification maps were then compared on a pixel-by-pixel basis using an $n \times n$ GIS "matrix" algorithm whose logic is shown in Figure 8. This resulted in the creation of "change images maps" consisting of brightness values from 1 to 81. The analyst then selected specific from-to classes for emphasis. Only a select number of the 72 (n^2-n) possible off-diagonal from-to land-cover change classes summarized in the change matrix (Fig. 8) were selected to produce the change detection maps (Fig. 9). For example, all pixels which changed from any land cover in 1982 to Developed Land in 1988 were color coded red (RGB=255, 0, 0) by selecting the appropriate from-to cells in the change detection matrix (10, 19, 28, 37, 46, 55, 64, and 73). Note that the change classes are draped over a TM band-4 image of the study area to facilitate orientation. Similarly, all pixels in 1982 that changed to Estuarine Unconsolidated Shore by 19 December 1988 (cells 9, 18, 27, 36, 45, 54, 63, and 72) were depicted in yellow (RGB=255, 255, 0). If desired, the analyst could highlight very specific changes, such as all pixels that changed from Developed Land to Estuarine Emergent Wetland (cell 5 in the matrix), by assigning a unique color look-up table value (not shown). A color-coded version of the change detection matrix can be used as an effective from-to change detection map legend (Jensen and Narumalani, 1992).

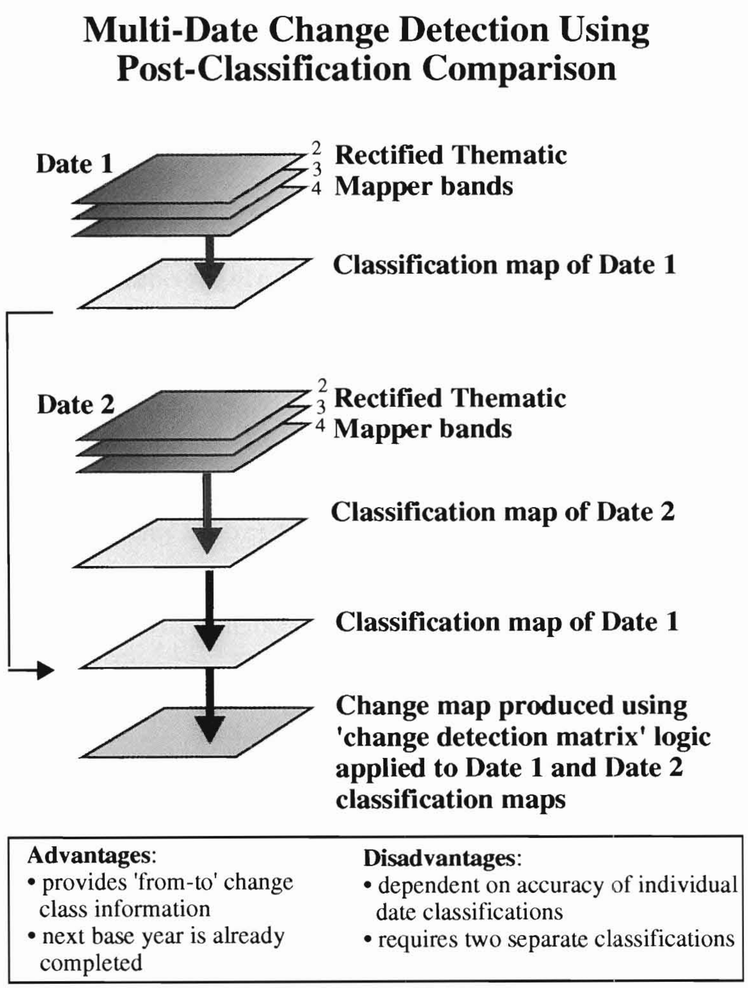


Figure 5
Diagram of Postclassification Comparison Change Detection (Jensen, 1994).

Postclassification comparison change detection is widely used and easy to understand. When conducted by skilled image analysts it represents a viable technique for the creation of C-CAP change detection products. Advantages include the detailed from-to information and the classification map for each year. Unfortunately, the accuracy of change detection is heavily dependent on the accuracy of the two separate classifications. Postclassification comparison is not recommended for C-CAP regional projects except under special circumstances, such as when different sensors are involved or when two separate organizations are classifying the same region at different times.

Multiple-date Change Detection Using a Binary Change Mask Applied to T_{b-1} or T_{b+1}

This method of change detection is highly recommended for C-CAP regional projects. First, the analyst selects the base image, T_b. Date 2 may be an earlier image T_{b-1} or a later image T_{b+1}. A traditional classification of T_b is performed by using rectified remote sensor data. Next, one of the bands (e.g. band 3 in Figure 10) from both dates of imagery are placed in a new dataset. The two band dataset is then analyzed by using various image algebra functions (e.g. band ratioing, image differencing, principal components analysis) to produce a new image file. The analyst usually selects a threshold value to identify spectral change and no-change pixels in the new image as discussed in "Image Algebra Change Detection." The spectral change image is then recoded into a binary mask file, consisting of pixels with spectral change between the two dates, and these are viewed as candidate pixels for categorical change. Great care must be exercised when creating the change/no-change binary mask (Dobson and Bright, 1993; Jensen et al., 1993a). The change mask is then overlaid onto T_{b-1} or T_{b+1} of the analysis and only those pixels which were detected as having changed are classified in T_{b-1} or T_{b+1}. A traditional postclassification comparison can then be applied to yield from-to change information. Hence, many pixels with sufficient change to be included in the mask of candidate pixels may not qualify as categorical land-cover change.

Dobson and Bright (1991, 1992, and 1993) used this change detection methodology to inventory change in the area surrounding the Chesapeake Bay using TM imagery obtained on 9 September 1984 and 3 November 1988

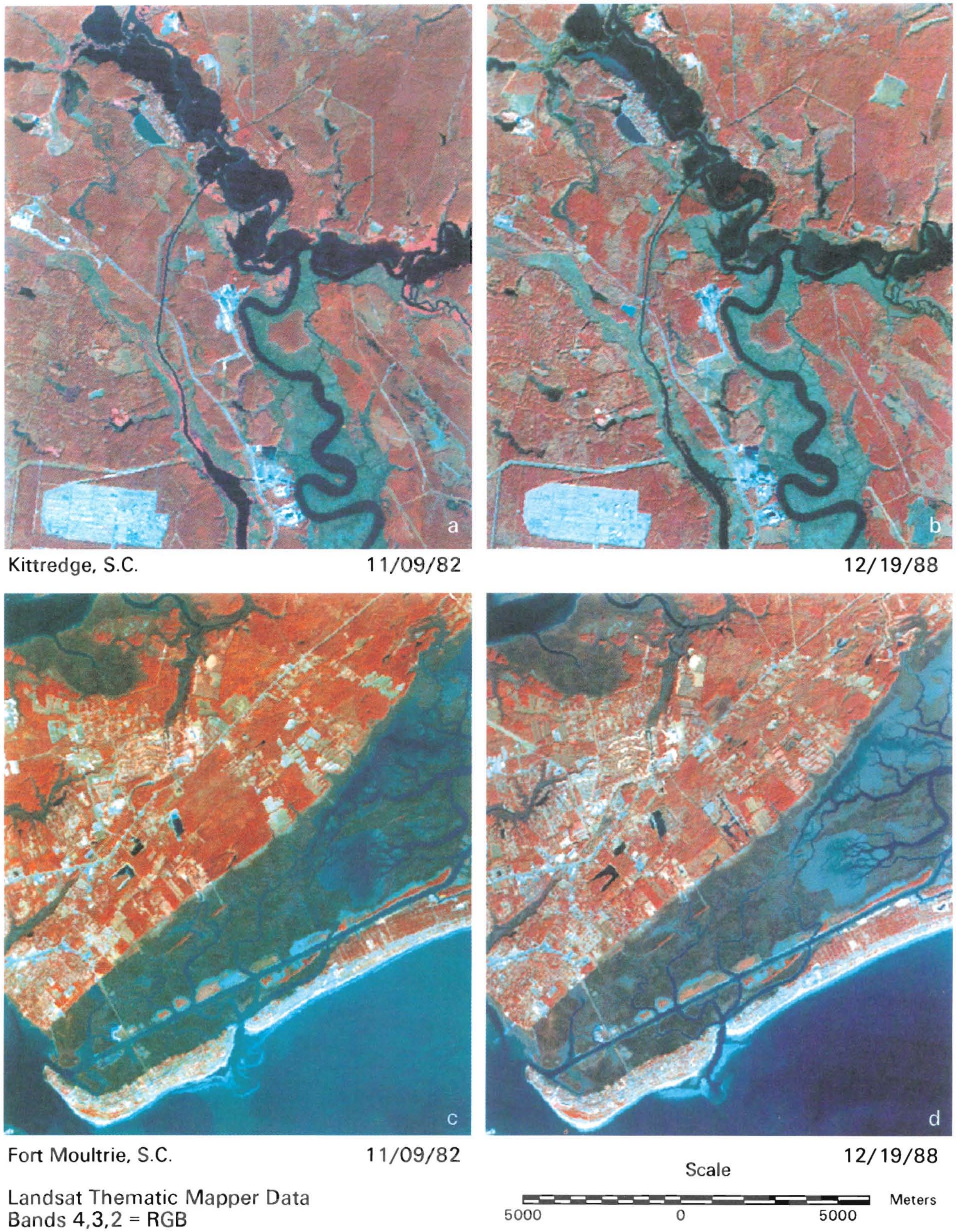


Figure 6

Rectified Landsat Thematic Mapper data: (a and b) obtained for the Kittredge, S. C., 7.5' quadrangle C-CAP study area, 9 Nov 1982 and 19 Dec 1988 (Jensen et al., 1993a) (c and d) Obtained for the Fort Moultrie, S. C., 7.5' quadrangle study area, 9 Nov 1982 and 12 Dec 1988.

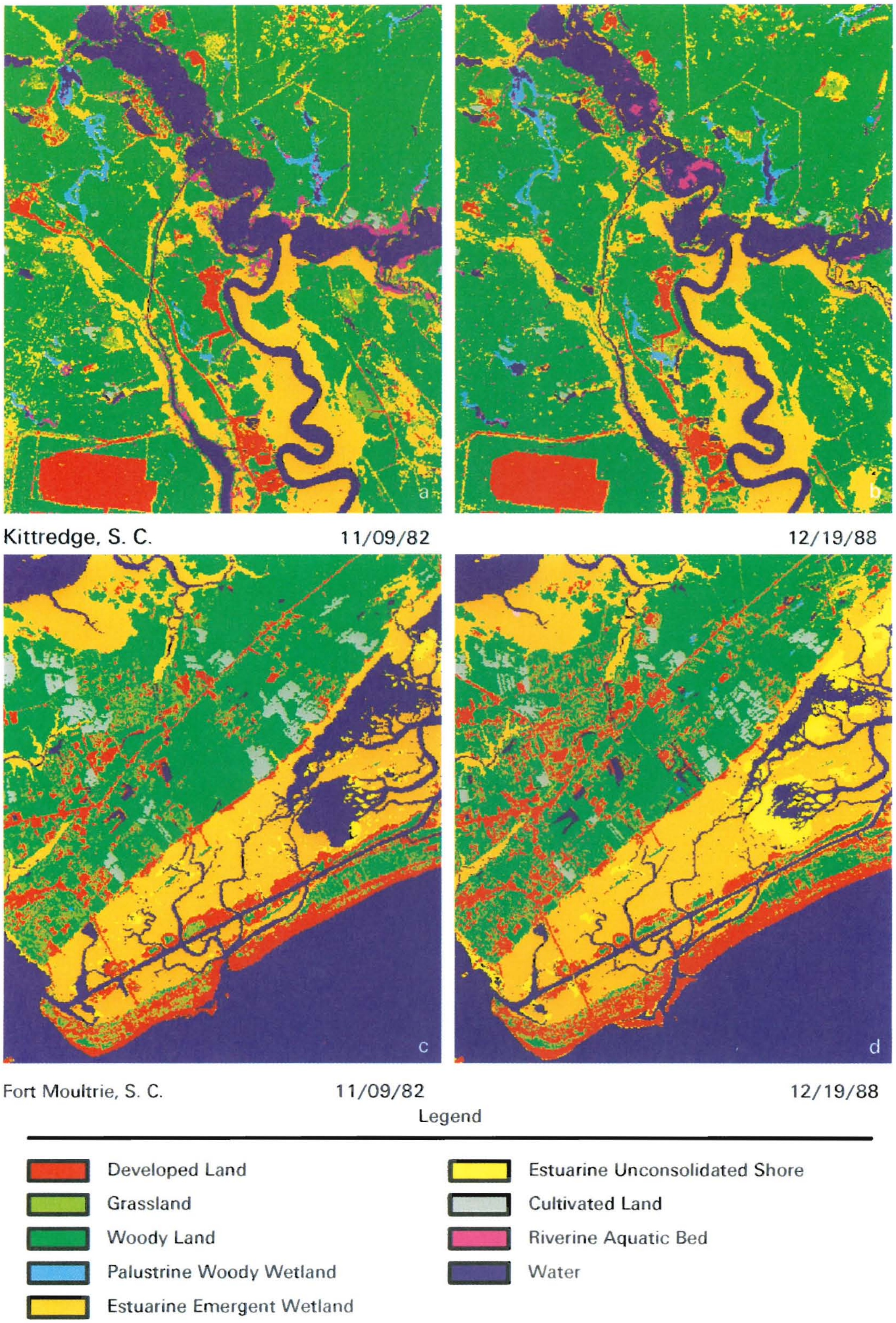


Figure 7

Multiple-date land-cover classification maps: (a and b) Kittredge, S. C., study area, produced from 9 Nov 1982 and 19 Dec 1988 Landsat TM data. (c and d) Fort Moultrie, S. C., study area, produced from 9 Nov 1982 and 19 Dec 1988 Landsat TM data (Jensen et al., 1993a).

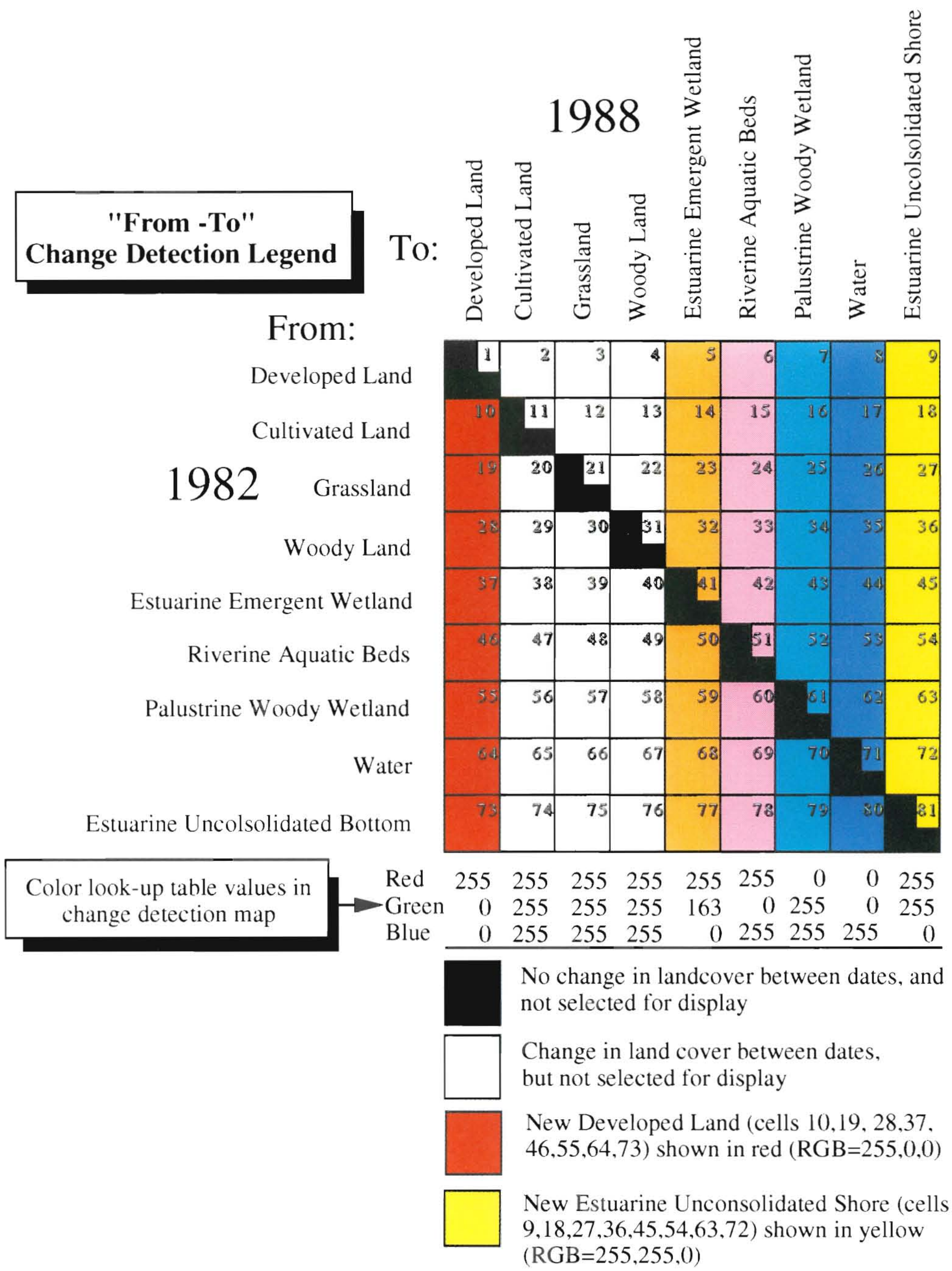


Figure 8

Change detection matrix. The basic elements of a change detection matrix may be used to select specific "from-to" classes for display in a "postclassification comparison" change detection map. There are $(n^2 - n)$ off-diagonal possible change classes which may be displayed in the change detection map (72 in this example) although some may be highly unlikely. The colored off-diagonal cells in this diagram were used to produce the change maps in Figure 9. For example, any pixel in the 1982 map that changed to Developed Land by 1988 is red (RGB=255,0,0). Any pixel that changed into Estuarine Unconsolidated Shore by 1988 is yellow (RGB=255,255,0). Individual cells can be color coded in the change map to identify very specific "from-to" changes (Jensen et al., 1993a).

(the region centered on Metomkin Inlet is shown in Figures 11 and 12). The 1988 base image was classified using traditional supervised classification techniques (Fig. 13). A change/no-change mask was derived by performing image arithmetic on bands 3, 4, and 5 of the two date dataset. All change pixels were combined into a single change mask (Fig. 14). The change/no-change mask was then overlaid onto the earlier date of

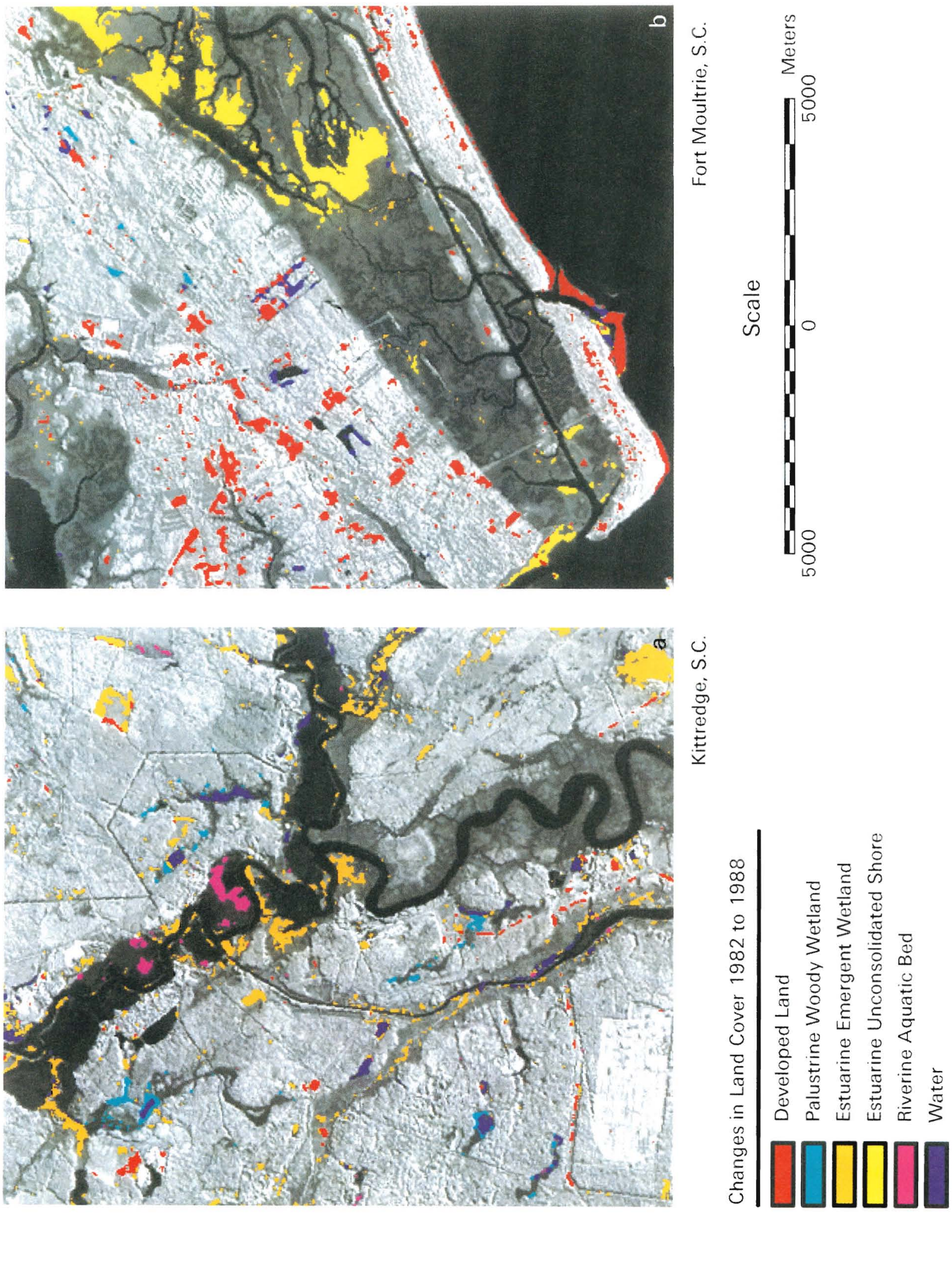


Figure 9
Change detection maps of the Kittredge and Fort Moultrie, S. C., study areas derived from analysis of 11 Nov 1982 and 19 Dec 1988 Landsat TM data. The nature of the change classes selected for display are summarized in Figure 8. The change information is overlaid onto the Landsat TM band 4 image of each date for orientation purposes (Jensen et al., 1993a).

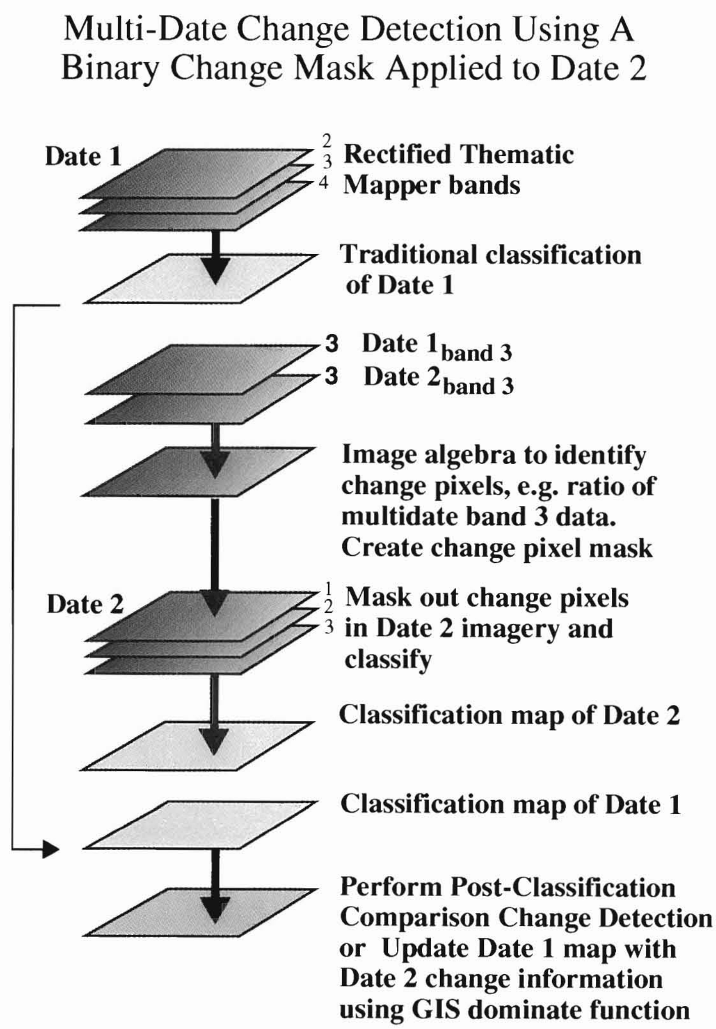
imagery and only those pixels which were detected as having changed were classified in the earlier image. A from-to matrix similar to the one shown in Figure 9 was then used to produce a change map of the region (Fig. 15). Summary statistics for the region are found in Table 4. This process may be repeated with a later scene to determine successive change.

This method may reduce change detection errors (omission and commission) and provides detailed from-to change class information. The technique reduces effort by allowing analysts to focus on the small amount of area that has changed between dates. In most regional projects, the amount of actual change over one to five years is probably no greater than 10% of the total area. The method is complex, requiring a number of steps, and the final outcome is dependent on the quality of the change/no-change binary mask used in the analysis. A conservative threshold may exclude real change while a liberal threshold may create problems similar to those of the post-classification comparison technique (See "Postclassification Comparison Change Detection.")

Multiple-date Change Detection Using Ancillary Data Source as T_b

Sometimes a land-cover data source may be used in place of a traditional remote-sensing image in the change detection process. For example, the NWI is inventorying all wetlands in the United States at the 1:24,000 scale. Some of these data have been digitized. Instead of using a remotely sensed image as T_b in the analysis, it is possible to substitute the digital NWI map of the region (Fig. 16). In this case, the NWI map would be "recoded" to be compatible with the C-CAP Coastal Land-Cover Classification System (Table 2). This should not be difficult since the two systems are highly compatible. Next, T_{b-1} or T_{b+1} of the analysis is classified and then compared on a pixel-by-pixel basis with T_b information. Traditional from-to information can then be derived. As with any other postclassification comparison, the accuracy of the change database is dependent on the accuracy of both input databases (C-CAP and NWI).

Advantages of the method include the use of a well-known, trusted data source (NWI) and the possible reduction of errors of omission and commission. Detailed from-to information may be obtained by using this method. Also, only a single classification of the T_{b-1} or T_{b+1} image is required. It may also be possible to update the NWI map (T_b) with more current wetland information (this would be done using a GIS "dominate" function and the new wetland information found in the T_{b-1} or T_{b+1} classification). The disadvantage is that the NWI data must be digitized and generalized to be compatible with the C-CAP Coastal Land-Cover Classification System, then converted from vector to raster format to be compatible with the raster remote-sensor data. Any manual digitization and subsequent conversion introduces error into the database which may not be acceptable (Lunetta et al., 1991).



Advantages:	**Disadvantages:**
• may reduce change detection errors (omission and comission) • provides 'from-to' change class information	• requires a number of steps • dependent on quality of 'change/ no-change' binary mask

Figure 10
Diagram of Multiple-Date Change Detection Using a Binary Change Mask Applied to Date 2 (Jensen, 1994).

Figure 11
Rectified Thematic Mapper imagery of the Metomkin Inlet area obtained on 21 Sep 1984 (Dobson and Bright, 1992).

Manual On-Screen Digitization of Change

Considerable amounts of high resolution remote sensor data are now available (e.g. SPOT 10 × 10 m, the aircraft mounted Calibrated Airborne Spectrographic Imager [CASI] of the National Aerial Photography Program [NAPP]). These data can be rectified and used as planimetric basemaps or orthophotomaps. Often aerial photographs are scanned (digitized) at high resolutions into digital image files (Light, 1993). These photographic datasets can then be registered to a common basemap and compared to identify change. Digitized high resolution aerial photographs displayed on a CRT screen can be interpreted easily using standard photo interpretation techniques based on size, shape, shadow, texture, etc. (Ryerson, 1989). Therefore, it is becoming increasingly common for analysts to interpret visually both dates of aerial photographs (or other type of remote-sensor data) on the screen, annotate the important features using heads-up on-screen digitizing, and compare the various images to detect change (Cowen et al., 1991; Cheng et al., 1992; Lacy, 1992; Wang et al.,

Figure 12
Rectified Thematic Mapper imagery of the Metomkin Inlet area obtained on 3 Nov 1988 (Dobson and Bright, 1992).

1992; Westmoreland and Stow, 1992). The process is especially easy when 1) both digitized photographs (or images) are displayed on the CRT side by side, and 2) they are topologically linked through object-oriented programming so that a polygon drawn around a feature on one photograph will also be drawn around the same feature on the other photograph. Scanning aerial photographs unavoidably reduces the spatial and spectral resolution of source data. This loss may be significant in photographs of submerged features, which are subject to interferences from aquatic as well as atmospheric sources. As with other new technologies, demonstration of the appropriateness of interpretation of scanned photographs will be a critical step in expanding the C-CAP Protocol (Also see "Accuracy Assessment for Individual Date Classification of Water and Submersed Habitat Data"). The manual on-screen approach is recommended as a useful adjunct to other change detection methods. Its principle drawback is the time required to cover large regions in such a labor-intensive fashion.

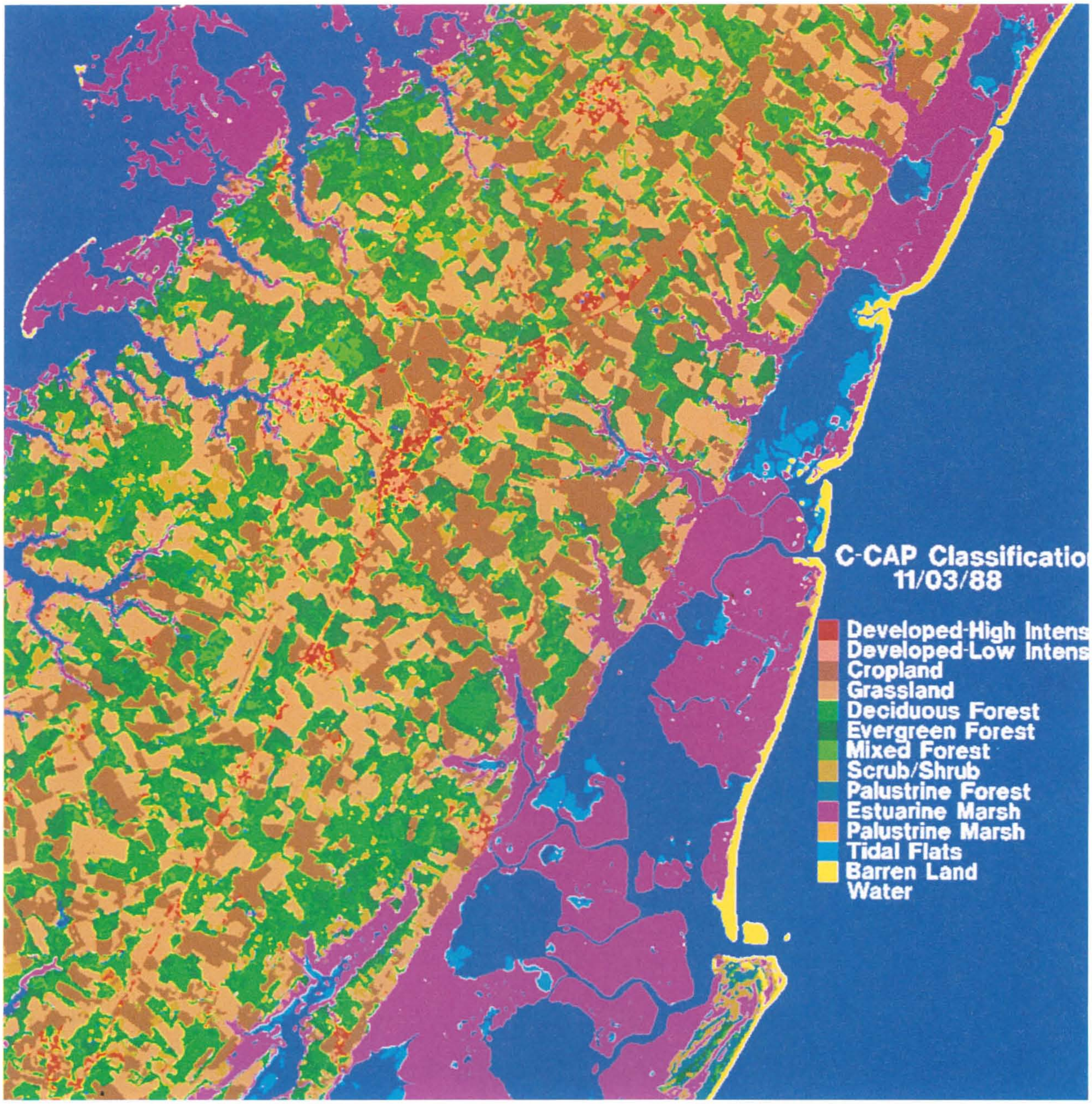


Figure 13
Classification map of 3 Nov 1988 Landsat Thematic Mapper imagery of the Metomkin Inlet area (Dobson and Bright, 1992).

Selecting Appropriate Classification Algorithms

C-CAP requires that the classification procedures used as part of the change detection process be approved and documented. Classification algorithms used in each region will be selected based on the capabilities and needs of the regional participants. C-CAP assumes that the regional participants are experienced in image processing and mapping. If not, C-CAP will attempt to provide fundamental technical assistance on a case-by-case basis.

The previous section indicated that these three of the seven most commonly used change detection algorithms are acceptable for C-CAP regional projects:

- Postclassification Comparison
- Change Detection Using a Binary Change Mask Applied to T_{b-1} or T_{b+1}
- Change Detection Using Ancillary Data Source as T_b.

Each of these requires a complete pixel-by-pixel classification of one date of imagery and, at least, a partial

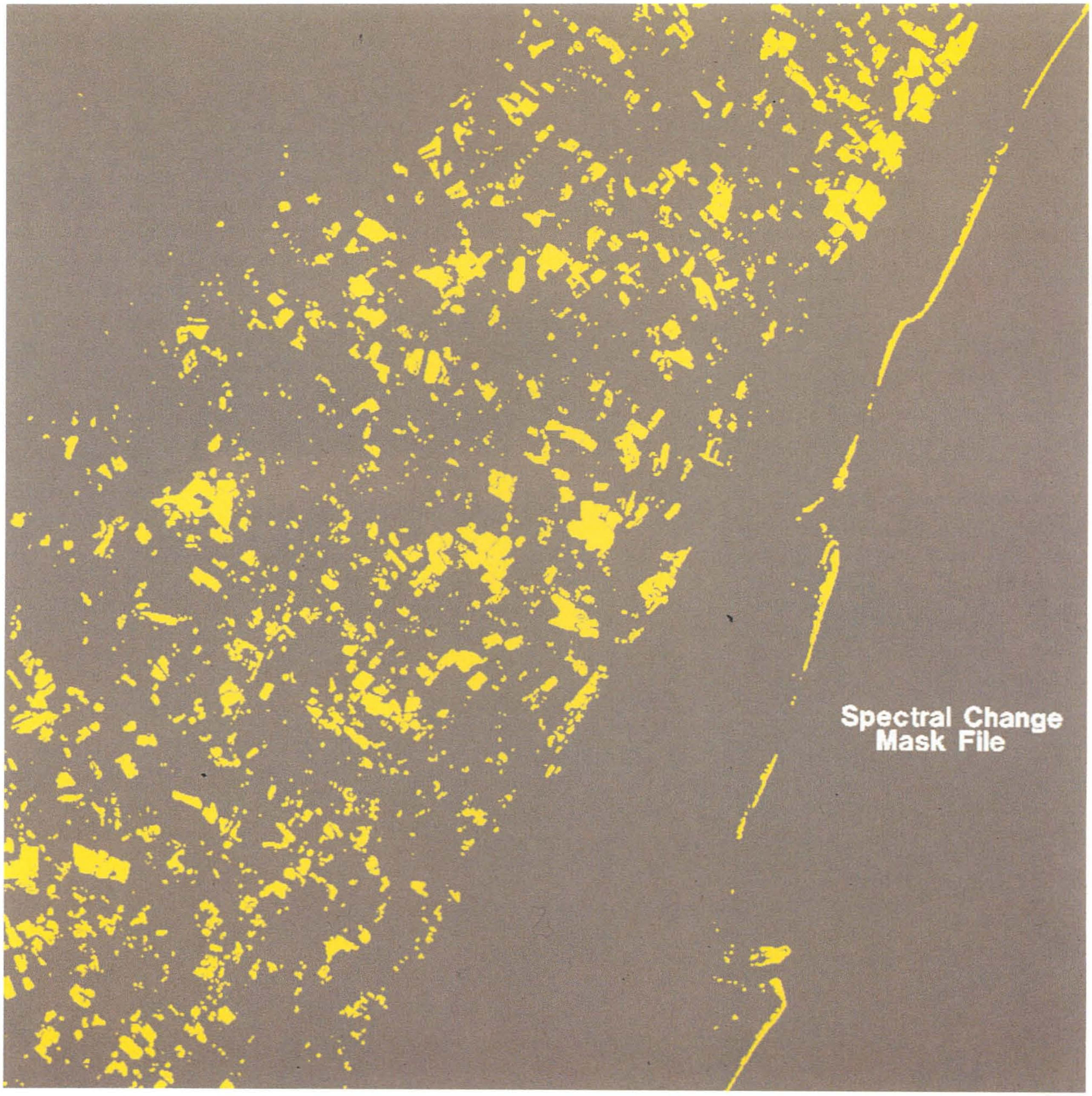


Figure 14

Binary "change/no-change mask" produced by image differencing TM bands 3, 4, and 5 of each date (Dobson and Bright, 1992).

classification of an additional date. Hence, it is instructive to review the C-CAP-approved image classification logic which may be used in the regional projects.

Supervised and Unsupervised Image Classification Logic

The primary reason for employing digital image classification algorithms is to reduce human labor and improve consistency. It is expected that regional analysts will have sufficient expertise to assess the advantages of alternative classification algorithms and to recognize when human pattern recognition and other types of intervention are necessary. In practice, it may be necessary to employ a suite of algorithms including both supervised and unsupervised statistical pattern recognition approaches. Currently, maximum-likelihood classifiers often serve as a good first step, but new statistical approaches are being developed and implemented on a routine basis (Jensen et al., 1987; Hodgson and Plews, 1989; Foody et al., 1992). It is important for analysts to remain flexible with regard to procedures and algorithms.

Standard supervised and unsupervised classification techniques have been available for more than 20 years and are well documented in texts by Jensen (1986) and Campbell (1987). In a supervised classification, the analyst "trains" the classifier by extracting mean and covariance statistics for known phenomena in a single date of remotely sensed data (Gong and Howarth, 1990). These statistical patterns are then passed to a minimum-distance-to-means algorithm in which unknown pixels are assigned to the nearest class in n-dimensional feature space, or passed to a maximum-likelihood classification algorithm that assigns an unknown pixel to the class in which it has the highest probability of being a member. Great care must be exercised when selecting training samples (Mausel et al., 1990).

In an unsupervised classification, the computer is allowed to query the multispectral properties of the scene by using user-specified criteria and to identify x mutually exclusive clusters in n-dimensional feature

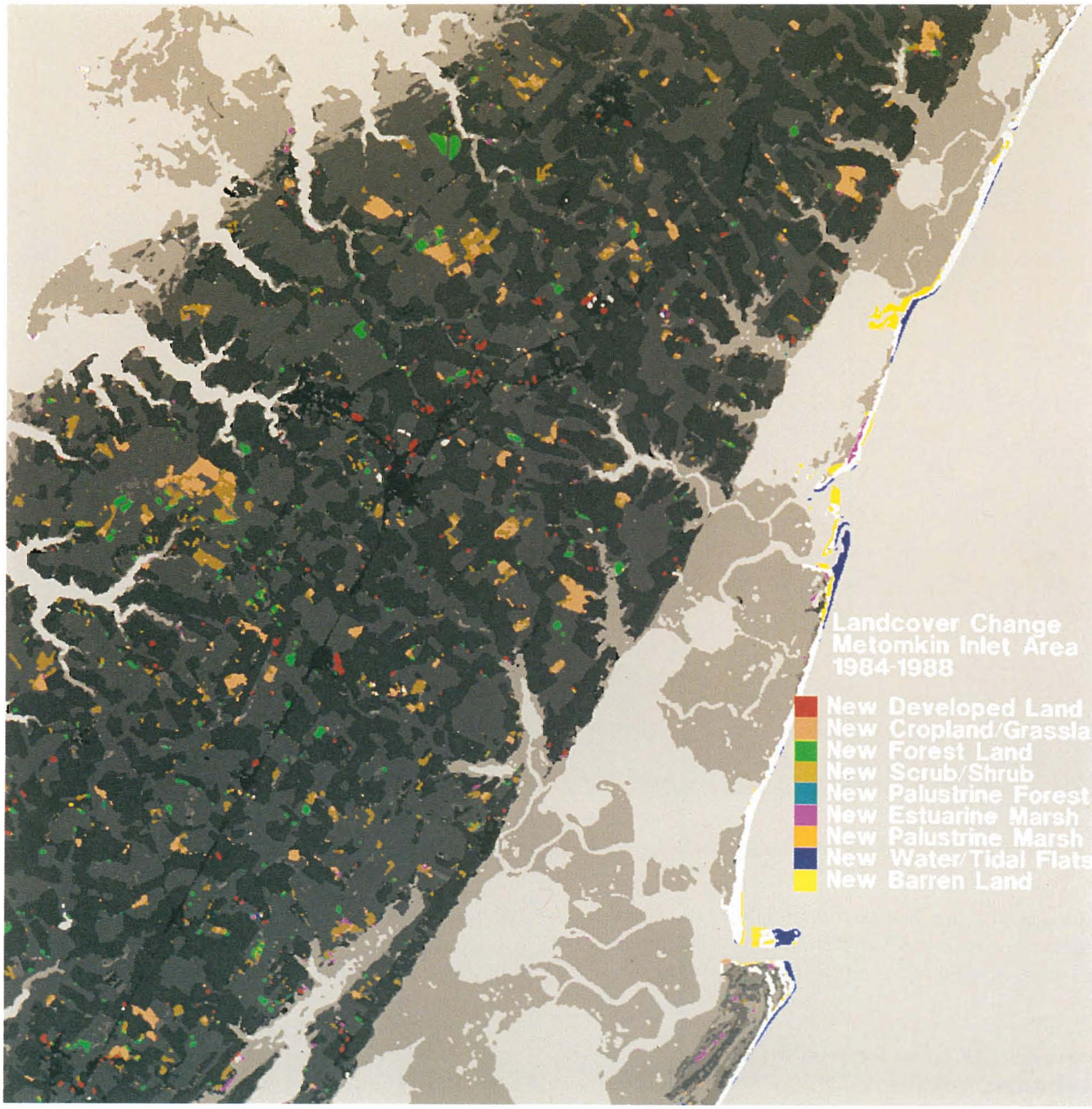


Figure 15

A map showing selected C-CAP change classes derived from analysis of the 21 Sep 1984 and 3 Nov 1988 Landsat TM data of the Metomkin Inlet area (Dobson and Bright, 1992).

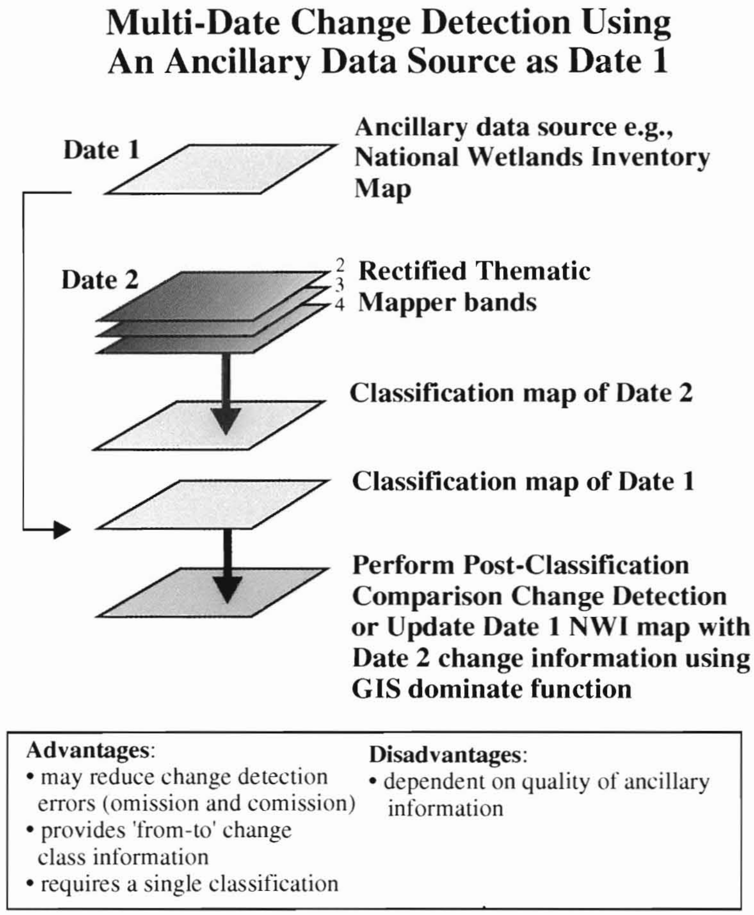


Figure 16
Diagram of Multiple-Date Change Detection Using Ancillary Data Source as Date 1 (Jensen, 1994).

space (Chuvieco and Congalton, 1988). The analyst must then convert (label) the *x* spectral clusters into information classes such as those found in the C-CAP Coastal Land-Cover Classification System. Training sites visited in the field and identifiable in the digital imagery are also indispensable when labeling clusters in an unsupervised classification. The following sections discuss C-CAP guidelines for collecting training and verification samples.

Selection of Training and Verification Samples for Supervised and Unsupervised Classification

Only training sites that were actually visited on the ground by experienced professionals should be selected for extracting the multispectral statistical "signature" of a specific class when performing a supervised or unsupervised classification. It is suggested that a minimum of five training sites per land-cover class be collected. This creates a representative training set when performing supervised classification and makes labeling clusters much easier in an unsupervised classification. In addition to the image analysts, the field team should contain specialists in ecology, biology, forestry, geography, statistics, and other pertinent fields, such as agronomy. Field samples should be stratified by land-cover type and by various physical factors such as slope, elevation, vegetation density, species mix, season, and latitude. The polygonal boundary of all field sites should be measured using GPS whenever possible, and the locational, temporal, and categorical information should be archived.

The collection of field training sites often requires multiple visits to the field. Some of the field sites may be used to train a classifier or label a cluster while a certain proportion of the field sample sites should be held back to be used for classification error assessment, which will be discussed.

Table 4

Statistical summary of areal change (in ha) by land-cover class for the Metomkin Inlet area shown in Figures 12–16. Read across each row to find which categories the 1988 totals came from. Read down each column to find which categories the 1984 totals changed to. Bold numbers along the diagonal indicate the area that did not change from 1985 to 1988. uncon. = unconsolidated.

	1984 Classification									
	Developed land	Grassland/ cultivated	Forest land	Scrub/ shrub	Palustrine forest	Estuarine emergent	Palustrine emergent	Water/ uncon. shore	Bare land	TOTAL
1988 Classification										
Developed land	**1,158**	85	8	0	0	4	0	1	0	1,256
Grassland/cultivated	0	**21,341**	562	0	0	2	0	0	17	21,922
Forest land	0	165	**18,915**	0	0	1	0	0	0	19,081
Scrub/shrub	0	240	562	**854**	0	2	0	0	0	1,658
Palustrine forest	0	20	9	0	**787**	0	0	0	0	816
Estuarine emergent	0	26	9	0	0	**11,587**	0	13	8	11,643
Palustrine emergent	0	0	0	0	0	0	**0**	0	0	0
Water/uncon. shore	0	4	0	0	0	2	0	**37,172**	144	37,322
Bare land	0	19	0	0	0	23	0	124	**507**	673
TOTAL	1,158	21,900	20,065	854	787	11,621	0	37,310	676	94,371

The following materials are indispensable to a successful field exercise:

- Imagery geocorrected to a standard map projection
- Topographic maps at 1:24,000 or the largest available scale
- Global Positioning System (GPS)
- Aerial photographs

It is advisable to perform, at least, a cursory classification before initiating fieldwork. In this case, both raw and classified data should be taken to the field. The primary function of the cursory classification is to guide field workers in targeting the covers and signatures that are most difficult and confusing. Keep in mind that the vast majority of all cover will be easy to identify on the ground and on the imagery. Efficient use of field time provides for quick verification of easy cover types and maximum attention to difficult, unusual, and ecologically critical cover types.

Field investigators should anticipate the need to know not only the geodetic coordinates of training sites but also the layout of the road network that will provide access. It is advisable to imbed roadway information into the raw imagery. This can be done using the Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER) files. Imbedding is preferred rather than transparent-overlay techniques, which are cumbersome and difficult to use under field conditions.

C-CAP investigators have assembled and tested a field station based on a color laptop computer with commercial software. At present the software supports visualization of raster imagery (e.g. satellite data, digital orthophotographs, scanned aerial photographs) and vector databases (e.g. TIGER road networks, NWI wetlands). A version of the software soon to be available from commercial vendors will allow realtime input of GPS coordinates. It will then be possible to follow field movements directly on the image and map data. The software also allows for completion of field forms on screen in the field. Preliminary tests are encouraging, but the field station is not fully operational at this time. One shortcoming, for example, is the poor performance of active matrix color screens in sunlight.

Use of Collateral Data in Image Classification

The overriding goal is to produce accurate individual date classifications and accurate change detection databases. Any information or operation that enhances data quality is generally encouraged. C-CAP does not endorse the notion that the use of collateral data in a remote-sensing project is "hedging." Instead, the objective is to use collateral data innovatively to improve the accuracy of the C-CAP database.

There are many potential sources of collateral data including soil maps, NOAA coastlines (T-sheets), timber surveys, USGS digital line graphs, and digital elevation models (for elevation, slope, and aspect). These can be incorporated by masking, filtering, probability weighting, or including in the signature file (Ryerson, 1989; Baker et al., 1991). Depending on the importance of each category, analysts may use certain categories to overrule others (Jensen et al., 1993a).

The NWI is an especially valuable collateral database that may be of value when classifying wetlands. Regional analysts should incorporate NWI data to the maximum extent possible. NWI data are recognized as the most authoritative and complete source of wetlands land-cover data (Wilen, 1990). However, NWI maps are not temporally synchronized in each region and are not in a digital format for many regions. An approach based on complementary use of NWI and imagery will be an asset to both C-CAP and NWI. At a minimum, NWI maps, digital data, or both should be used to define training samples, to check intermediate results, and to aid in the final verification of the wetlands portion of the C-CAP maps. NWI digital data may be used as a probability filter in the classification process. In this approach, C-CAP recommends an "innocent until proven guilty" attitude toward the NWI data. In other words, the NWI category is considered correct for a given pixel area for each time period, unless spectral signatures or collateral data suggest that the NWI category is incorrect or a land-cover change has occurred. Even if the NWI data were 100% correct at the time of NWI mapping, overriding by spectral data would be necessary to detect change over time. Ultimately in turn, the C-CAP change detection database can assist NWI managers in determining the need for NWI updates.

Cartographic Portrayal of Classification and Change Detection Maps

C-CAP products must meet stringent cartographic standards. The following sections discuss the minimum measurement unit and its proper use when aggregating change information. Formats of classification maps and change maps must satisfy C-CAP criteria whenever hardcopy maps are produced.

The Concept of the Minimum Measurement Unit

The minimum measurement unit is a measure of both the precision and accuracy of input data. For most C-CAP regional projects, the input data will be 30 × 30 m pixel data recorded by a Landsat TM sensor. The minimum measurement unit, however, combines the ability (e.g. sensor limitations) and effort (e.g. field verification) required to measure a category with the spatial precision and accuracy necessary to accomplish the intended use of the data. Each land-cover category could potentially have a different minimum measurement unit based on the size of individual parcels and the distinctiveness of the signature. Thus, the minimum measurement unit differs from a traditional minimum mapping unit, which by definition imposes a predetermined polygon (or pixel) size for all land-cover categories (for example, a rule that all parcels of one hectare or larger will be mapped). This traditional approach is acceptable for manual mapping using analog aerial photographs but is difficult to apply to raster imagery. Regional analysts will be responsible for defining minimum measurement units, which will generally be larger than a single pixel but no larger than three pixel dimensions on the short axis.

Regardless of the minimum measurement unit, change analysis will be conducted pixel by pixel. C-CAP protocol requires that the inherent resolution of the raw data must be retained throughout the classification and change-analysis processes. Aggregation and filtering of pixels should occur only in regard to cartographic presentation of the completed change detection database.

Regardless of the techniques employed, the final database should be capable of representing land-cover by class for the base time, land cover by class for each earlier or later time, and land-cover change by class for each change period. The final database should contain the full change matrix (all "from" and "to" categories) for each change period.

Analog (Hardcopy) Cartographic Products

Hardcopy maps of the final database are not specifically required by C-CAP, but they are certain to be useful when presenting results. Often it is useful to produce a smaller scale regional map (usually requiring some pixel aggregation) that gives an impression of the scope of the effort and to produce several larger scale maps at full resolution that demonstrate the level of detail and highlight notable findings. All maps should come directly from the final database complying with C-CAP protocols, but overlaying or imbedding ancillary data, such as DLG and TIGER data, is encouraged with proper notation.

If the statistical summary of changes is present on a map, C-CAP recommends that the numbers included in it always be calculated for the area shown on the map. It is not acceptable to associate the summary of changes for one area (larger or smaller) with a map of another. The statistical summaries of the change detection matrix must always be calculated from the database at full resolution, rather than from the aggregated data of the plot file. It is not advisable to allow the numerical count of class area to float with the level of cartographic aggregation. Unless all counts are based on the full resolution database, some classes composed of small features may disappear at higher levels of aggregation. Map readers may become confused if matrix numbers change with aggregation for the same territory.

Technically, the minimum cartographic presentation is 1) a map for the base time, 2) a map showing gains by class, and 3) a map showing losses by class. A full classification for the earlier or later (nonbase) time may be useful, but it is not essential to present the matrix of possible changes. Examples of some of these products are found in Figures 6–13.

Chapter 4
Monitoring Submerged Land Using Aerial Photography

C-CAP Focus on Aerial Photography of Submersed Rooted Vascular Plants (SRV)

Photic submerged land can support submersed rooted vascular plants (SRV) (including salt-requiring seagrasses and oligohaline and freshwater tolerant grasses and forbs), macroalgae, and coral reefs (see "Water and Submerged Land" and Appendix 3). The C-CAP Coastal Land-Cover Classification (see Table 1) identifies Marine/Estuarine Aquatic Beds, specifically SRV, of primary importance to be inventoried and placed in the C-CAP database (Klemas et al., 1993). Many of the steps discussed in Chapter 3 to monitor uplands and wetlands are pertinent to monitor SRV. However, there are significant differences which cannot be ignored (Table 5). Important considerations include the following:

- mapping SRV is primarily a photogrammetric task, rather than a satellite task, requiring an entirely different sensor system (aircraft, camera filter, and film);
- aerial photography is normally not radiometrically (except for color balance between photographs) or geometrically corrected;
- time of day, sensor altitude, and flightline placement are very flexible, unlike fixed orbit satellite sensor systems;
- numerous environmental conditions must be considered (sea state, water clarity, water depth, low altitude atmospheric conditions) to optimize photography; and
- aerial photographs are in analog format.

These differences are so significant that it is instructive to focus on aerial photography of SRV.

Ancillary Categories of Submersed Habitat

Other types of submersed habitat classified by C-CAP can be monitored with guidelines similar to those presented here for SRV. At a minimum, regional cooperators are requested to map and conduct change analysis for SRV. Increasing the number of habitat types to be included in the study will be based on local or regional interest and support for the effort. For example, a comprehensive mapping of SRV, macroalgae, and coral reefs is underway in the Florida Keys (see "State of Florida, Department of Environmental Protection").

Ancillary Technologies for Collecting Submersed Habitat Data

Some successes have been reported with satellite imagery and a number of other technologies in monitoring photic submerged land. Presently, these technologies supplement, and eventually may replace, aerial photography for change detection in SRV. Some of them are briefly mentioned here.

Satellite imagery has some advantages and disadvantages compared with photography. Satellite data generally have greater spectral resolution than aerial photography but lesser spatial resolution. Satellite imagery is already in a digital format whereas information derived from aerial photography must eventually be digitized to be quantitatively analyzed. Landsat and SPOT data have been successfully used to inventory some macroalgae such as the giant kelp, *Macrocystis pyrifera*, along southern California shorelines (Jensen et al., 1980; Augenstein et al., 1991). In clear shallow tropical waters with highly reflective substrate, Landsat imagery may discriminate sandy from coral reef or seagrass areas (Luczkovich et al., 1993) or provide an estimate of biomass for unispecific beds of *Thalassia testudinum* (Armstrong, 1993). In the turbid estuaries of the eastern United States, Landsat and SPOT imagery can be used to detect some (e.g. large, dense, shallow) but not all of the SRV that is visible in the best aerial photography. Aerial photography is, in fact, often used as "ground truth" when interpreting satellite imagery. Because of the fixed orbital paths of satellites, it is only fortuitous when a satellite image is acquired under optimum conditions to inventory SRV (see "Environmental Considerations"). For these reasons, aerial photography is the C-CAP imagery of choice for comprehensive mapping and change detection (Ferguson and Wood, 1990; Thomas and Ferguson, 1990; Orth et al., 1991; Ferguson et al., 1992 and 1993). Photo interpretation supported by surface-level signature verification and species identification is qualitatively and spatially more reliable for SRV than are satellite-based methods.

Several technologies may provide valuable supplemental data to aerial photographic detection of habitat change. These include closed circuit television (CCTV) on an airplane, small boat, or remotely operated vehicle (ROV), side-scan and down-looking sonar, new satellite sensors, airborne spectral scanners and digital video scanners, and digitized photography. Such new

Table 5

General steps required to conduct regional C-CAP change detection projects to extract water and submerged land information using aerial photography. Each major step is listed in the order to be accomplished.

1. **State the regional change detection problem**
   a. Define the region
   b. Specify frequency of change detection (1 to 5 yr)
   c. Identify classes of the C-CAP Coastal Land-Cover Classification System

2. **Consider significant factors when performing change detection**
   a. Remote sensing system considerations
      1) Spatial resolution and scale
      2) Flightline considerations
      3) Spectral resolution and film/filter combination
      4) Temporal resolution and diurnal sun angle
      5) The preferred C-CAP aerial photography system
   b. Environmental considerations
      1) Atmospheric conditions
      2) Turbidity conditions
      3) Vegetation phenological cycle characteristics
      4) Tidal stage
      5) Surface roughness and sun glint conditions

3. **Interpret aerial photographs to extract water and submerged land information**
   a. Acquire appropriate change detection data
      1) In situ surface level verification and basemaps
      2) Aerial photography
         a) Base year (T_b)
         b) Subsequent year(s) (T_{b-1} or T_{b+1})
   b. Preprocess the multiple-date photography
      1) Radiometric correction (color balance)
      2) Optically register photography to planimetric basemap
   c. Select appropriate change detection algorithm (usually postclassification comparison)
   d. Image analysis
      1) Monoscopic (interpretation of single photos or orthophotographs)
      2) Stereoscopic (analog or analytical)
   e. Transfer polygons to planimetric basemap
   f. Digitize polygons
   g. Perform change detection using GIS algorithms
      1) Highlight selected classes using change detection matrix
      2) Generate change map products
      3) Compute change statistics

4. **Conduct quality assurance and control**
   a. Assess spatial data quality
   b. Assess statistical accuracy of
      1) Individual date classification
      2) Change detection products

5. **Distribute C-CAP results**
   a. Digital products
   b. Analog (hardcopy) products

technology will be incorporated into the C-CAP guidelines as it is demonstrated to meet qualitative, quantitative, resolution, and geographic positioning standards. At present, CCTV is effective for surveillance applications but georeferencing and rectification fall short of metric quality photography. Airborne multispectral scanners and digital cameras are technologies with applications in the demonstration stage of development.

Direct mapping of habitat borders can be performed with differentially correctable GPS instrumentation when the perimeter of that habitat can be visually observed or detected with the aid of instruments in the field. Differentially corrected GPS can provide positions of surface level data at an accuracy suitable to supplement or assess the accuracy of aerial photographic data. With differential correction, single position fixes with GPS are accurate to a circular error probable (CEP)of ±5 m 50% of the time. The methodology for using GPS in accuracy assessment and monitoring of SRV is a current research topic funded by C-CAP.

Aerial Photography of SRV

Film

The recommended film for aerial photography of SRV is Aerocolor 2445 color-negative film. Second choices are Aerochrome 2448 color-reversal and Aerographic 2405 black-and-white negative film. A haze filter should always be used to minimize the degrading effect of haze on photographic images. We do not recommend infrared film for delineating SRV. In our experience in North Carolina with tandem cameras, Aerochrome 2443 false-color infrared film was much less effective than color film at recording benthic features in shallow, moderately turbid water. True color film gives more information than black-and-white or infrared film, is critical for initial mapping attempts in new or unfamiliar areas, and may permit identification of species in some tropical areas. Color negative film also appears to be better than color reversal or black-and-white film for identification of habitat under moderately turbid or hazy conditions. Color transparency prints are dimensionally stable and are most amenable to illuminating dark areas of the photograph under magnification. Paper prints are not as dimensionally stable as transparencies (i.e. paper prints are subject to stretching and shrinking) but they are more resistant than transparencies to damage from handling when used for field work.

Metric Photography and Photographic Scale

Metric-quality aerial photographs (≤3° of tilt off-nadir and including camera calibration data) are essential and should be acquired with a protocol similar to that employed by NOAA's Photogrammetry Branch (1980) to produce the highest quality data possible. The need for rectification of photography is minimized by precise control of aircraft altitude and orientation relative to the vertical during photography and by interpretation in stereo. Photography should be obtained at a scale appropriate to the areal extent of habitat, local water conditions, type of habitat being studied, and resolution requirements for the resultant data. Scale is a compromise among resolution of signatures, coverage of habitat, inclusion of land features sufficient for horizontal control, and cost. Photographic scale should normally range from 1:12,000 to 1:24,000. For extensive areas of high and variable turbidity such as Chesapeake Bay and eastern North Carolina, 1:24,000 or 1:20,000 scale photographs may be adequate when the water is clear. For chronically turbid estuarine or brackish water areas, 1:12,000 or larger scale photographs obtained at times of minimal turbidity may be required for acceptable visualization of submerged features. Small-scale photography may be necessary to bridge habitat delineated in larger scale photographs to local horizontal control points on adjacent land features that are not included in the larger scale photographs. GPS onboard the airplane for positioning photographic centers during exposure may reduce this limitation of larger scale photography. For extensive areas of relatively clear water, such as the Florida Keys, a scale of 1:48,000 may be sufficient and cost effective. This is a current C-CAP research topic (see "State of Florida, Department of Environmental Protection").

Flightlines, Reconnaissance Flights, and Photographic Overlap

Flightlines are planned with reference to aeronautical and nautical charts to include all areas known to have, or which potentially could have, SRV. The efficiency of photographic missions can be optimized by minimizing the number of flightlines and by contingency planning. Some airspace is restricted for military or other use, for example, and is indicated on aeronautical charts. Nautical charts provide bathymetric data useful for designating potential habitat areas when combined with local knowledge of the depth of vegetated bottoms. Reconnaissance flights can provide valuable perspective on SRV distribution if timed to optimize visualization of shallow bottoms (see "Environmental Considerations"). Ideally, each photograph in a flightline records cultural and shoreline features required to register the image to the base map, about 1/3 of the exposure. This permits correction of photographic scale and orientation to the external reference system. At a scale of 1:24,000 (1 inch = 2,000 ft), a standard 9 × 9 inch aerial photograph has a coverage of 18,000 × 18,000 ft. Large areas (relative to coverage of a single photograph) of open water require parallel flightlines and bridging of the large-scale photography to control points with the small-scale photography, construction of towers, etc., to supplement horizontal control features or inflight GPS positioning of photographic centers.

Overlap of photographs includes endlap of adjacent photographs along a flightline and sidelap of photographs along parallel flightlines. Sixty percent endlap allows stereoscopic interpretation, facilitates interpretation from the most central region of the photographs, and compensates for loss of coverage due to sun glint in the photographs. (Sun glint is the image of the sun reflected off the surface of the water. See "Sun Angle.") Sidelap of 30% ensures contiguous coverage of adjacent flightlines and produces a block of aerial photographs that may be subjected to photogrammetric bundle adjustment if necessary.

Environmental Considerations

Knowledge of the study area that is important to a successful project includes the plant species comprising SRV; morphology and phenology of these plants; depth range and location of known habitat; locations with water depth potentially suitable for habitat, types and locations of benthic features that may confuse photo interpretation of SRV; seasonality of turbidity, weather, and haze; daily patterns in wind speed and direction; and progression of sun angle through the day. Primary and secondary seasonal windows and the day and time to conduct photography are selected to optimize the visibility of habitat in the photography. Surface waters in different locations and at different times of the year will be more or less sensitive to turbidity from local runoff, plankton blooms, local resuspension of sediment, and surface waves. Seasonal and daily trends for haze, cloud cover, wind direction, wind duration, and wind velocity should be included in planning for photography. The decisions of when to have the aircraft arrive at the study area (within the seasonal window) and when to collect photography are based on NOS tide tables, local knowledge of factors affecting water clarity and depth, observation of recent weather patterns (precipitation, wind direction, and wind speed), and water clarity. The final decision to photograph includes observations from the air based on the pilot's estimate of haze, cloud cover, and overall visibility.

Primary and secondary photographic windows should be one or two months duration to ensure optimal conditions for photography. For single day missions it may be possible to have the plane and flightcrew fly to the study area on the day of photography. In our experience in North Carolina, staging of the plane and flight crews to the study area several times for several days was required to complete missions involving more than one day of actual photography.

Phenology—The best time of year to acquire photography is during the season of maximum biomass or flowering of dominant species, considering the phenologic overlap for the entire community. This is June for the SRV of the Pacific Northwest and Atlantic Northeast, April and May for eelgrass in eastern North Carolina, and September for most of the other species of SRV in the eastern United States.

Clouds and Haze—It is best to have no clouds and minimal haze. Thin broken clouds or thin overcast above the plane may be acceptable when these are determined by visualization from the air neither to cast shadows nor adversely affect illumination of the study area. Haze reduces illumination and clarity of the image of benthic features being recorded in the photograph. Cooperators are referred to the "Aerial Photographers Clear Day Map," U.S. Department of Commerce, Environmental Data Service.

Turbidity—Aerial photography should be conducted when turbidity is low. Care should be exercised in areas adjacent to sources of suspended sediment and nutrients. Data collection should be avoided during seasonal phytoplankton blooms or immediately following heavy rains or persistent strong winds. Potential days for photography are those during the photographic window when high water clarity is expected, based on local experience, recent weather patterns, and surface level observation. The flightcrew should confirm water clarity from the air on the day of photography.

Tides—Generally, aerial photography should be collected within ±2 hours of the lowest tide predicted by NOS tide tables, although factors affecting water depth and water clarity should be considered simultaneously. In general, extreme low tide, which may be –0.5 to –1.0 m or more around the U.S. coast is preferred, if compatible with other constraints. The significant "lag" in the tidal stage of some estuaries should be considered for data acquisition.

Wind and Surface Waves—No wind and no waves is best for aerial photography. Low wind (<10 mph) may be acceptable. The direction, persistence, fetch (the distance that wind can blow unobstructed over water), and recent wind events should be taken into account. Breaking waves and associated turbidity, white caps, lines of bubbles, and floating debris should not be visible from the air or in the photographs. For some areas, ocean swell can be an important consideration and should not exceed 3 ft.

Sun Angle—Sun angle affects the illumination of benthic features, sun glint, and shadows from tall shoreline features in the photographs. A sun angle of 20–25° is optimal to record benthic features (Keller, 1978). A sun angle of 15–30° is recommended by C-CAP. This interval maximizes the time for photography considering both the illumination of submerged features and sun glint. Sun angles above 15° illuminate the bottom sufficiently for photographic purposes. Sun glint also increases with sun angle but precludes visualization of benthic features where it occurs in the photograph. As sun angle increases, sun glint also increases and moves from the edge toward the center of the photograph. Loss of coverage due to sun glint at sun angles of up to about 30° is compensated (to ensure monoscopic coverage, at a minimum) by the recommended endlap of 60% (see "Flightlines, Reconnaissance Flights, and Photographic Overlap"). Eighty percent endlap will improve coverage when high sun angles cannot be avoided. Photography at sun angles above 30° is not recommended. Sun glint is minimized when the sun and land are on the same side of the plane because sun glint does not occur on land. Shadows from tall objects on shore such as trees, however, can preclude visualization of benthic features and may be a factor when the land and sun are on the same side of the plane.

Photointerpretation of SRV

Habitat defined by the presence of SRV can be interpreted from metric-quality aerial photographs exposed as recommended in the previous sections. The accurate identification of SRV in aerial photographs requires visual evaluation of the fundamental elements of image interpretation (tone, color, contrast, texture, shadow, etc.). It also requires extensive experience at ground level in the study area; the photographic images of habitat and nonhabitat features vary in ways which cannot readily be modeled, described, or communicated. Training for a habitat change analysis effort includes literature research; discussions with local ecologists and biologists; site visits on foot, swimming (snorkel or scuba), or small boat; overflights in a small plane; and examination of historical aerial photographs of the area. Training of photo interpreters is active throughout the life of the project.

SRV are best observed by using stereo pairs of photographs and high quality stereoscopic instruments (e.g. Wild, AVIOPRET, APT2, stereoscopes). Polygons are traced on overlays fixed to each photograph. To be delineated as habitat, recognizable and verified signatures of SRV must be present in the photographs. SRV (and other benthic features) in a given area will present a variety of signatures depending upon the species present, bottom sediment, depth, season, haze, clouds, water clarity and surface disturbances, and sun angle at the time of photography.

The designation of a given area as SRV is a function of the minimum detection unit, the minimum mapping unit, and the proximity of the area to other SRV. Assuming a photographic scale of 1:24,000, high quality optics, high resolution film, and ideal conditions (e.g. dense clusters of large vigorous shoots growing on light-colored sediment in shallow, clear, calm water), it is usually possible to have a minimum detection unit of approximately 1 m. All detected SRV that appear to be in a continuum with adjacent SRV in an area exceeding 0.03 ha will be mapped as a single polygon. The minimum mapping unit is the smallest area to be mapped as habitat. At the C-CAP map scale of 1:24,000, the minimum mapping unit is 0.03 ha for SRV (i.e. a diameter of about 0.8 mm on the map represents a diameter of about 20 m or an area of about 0.03 ha on the ground). Therefore, isolated groups of shoots with a diameter of less than 20 m may be detected but not mapped as habitat. The presence of SRV signature in the photograph defines habitat if 1) the total area exceeds 0.03 ha; 2) no unvegetated discontinuities, such as dredged or natural channels, partition the distribution into spatial units less than 0.03 ha; and 3) unvegetated areas between plants are not large relative to the minimum mapping unit. Unfortunately, not all areas of SRV can be detected when photographic conditions are less than ideal. Because of the constraint of the minimum mapping unit and the possibility of suboptimal photography, delineations of SRV will tend to be conservative. The degree of underestimation depends upon the atmospheric and hydrographic conditions at the time of photography, the experience of the photo interpreter, and the nature of the subject area.

Optimizing conditions for photography will minimize underestimation of SRV, particularly in areas that are intrinsically more difficult to interpret. Where habitat edges are clearly distinct in superior-quality photography, they may also be detected in inferior-quality photography (e.g. high biomass of SRV along a clear water channel with a steep bank of light-colored sediment). In other cases where the edges are not clearly distinct in superior-quality photography, they are likely to remain undetected in inferior photography (e.g. low biomass of SRV growing on a shallow depth gradient of deep, turbid water over dark-colored sediment). The deep-water edge of habitat often will be difficult to delineate. This edge may also be at high risk for loss due to degradation in water quality that limits the illumination of the bottom with photosynthetically active radiation.

SRV with unrecognized signatures due to poor photographic conditions cannot be mapped as habitat unless the area is rephotographed or additional sources of data are incorporated into the database. When photo interpretation is difficult or not possible, the preferred option is to rephotograph the area under better conditions. Although desirable, this may not be possible. Even under the best photographic conditions, delineation of all or part of some habitat polygons may require additional effort in regard to surface level verification or direct inclusion of surface level data. Polygon borders derived from surface level data must be so designated in the lineage database for "truth in labeling" requirements (see "Digital Product"). Suitable surface level positioning techniques include GPS or more traditional survey positioning techniques that can be demonstrated to provide the positional accuracy required by C-CAP.

Within a polygon of SRV, the extent of bottom coverage by shoots of SRV and the pattern of distribution of the shoots or bed form (e.g. circular, doughnut-shaped, irregular patches, or continuous cover of SRV) reflects the interaction of biotic, physical, and anthropogenic factors. Coverage and bed form can be estimated from aerial photographs but is not a requirement of C-CAP. An example of a coverage index is an adaptation of the crown density scale originally developed to categorize coverage by trees crowns in forests (Orth et al., 1991). However, coverage indices and bed-form identifications are affected by factors such as water depth and brightness of bottom sediments. The degree of contrast between shoots and exposed sediment and the clarity of the photographic image determines the minimum detection unit of features within SRV. Comparison of habitats with different depths, water clarity, or substrate brightness, therefore, is problematic. Analysis of change over time at a given location may be useful but requires consistent photographic conditions and field verification. Changes in coverage or bed form over time in a given location may indicate changing conditions in that habitat polygon or disturbances, such as scarring by boat propellers.

Some data including species, biomass, productivity, functional status, and health of SRV may not be interpretable from the aerial photographs. Species identification is not possible from aerial photography in temperate areas such as North Carolina and the Chesapeake Bay. In some tropical areas, species distributions and photographic signatures may be sufficiently distinct to discriminate by species.

Field Surveys

Species and Habitat at Randomly Selected Stations

Once selected by stratified random sampling of potential habitat, stations are observed for SRV species and the presence or absence of aquatic beds during the same season and preferably within one year of the photography. Stations are stratified by water depth and water body. Water depth determines if sampling can be accomplished by wading, snorkeling, or scuba diving. Clear water with a bottom depth of ≥2.5 m or somewhat shallower turbid water may require scuba. Stratification permits flexibility in sampling intensity and effort (sampling by scuba requires special training and resources and takes about twice the time per station). Bathymetry and reference coordinates in NOAA nautical charts of the study area facilitate selection and positioning of stations. Navigation to stations is with GPS. The spatial density of points is adjusted according to the resources and scale of the project (e.g. an average of 1.5 to 2.5 nmi from station to station in North Carolina). Great care is taken to include all locations of potential habitat in the surface level survey. SRV are limited to water depths less than about 2 m at mean lower low water (MLLW) for Chesapeake Bay. A similar depth limit was determined for that habitat in eastern North Carolina. To determine that depth in North Carolina, potential habitat was sampled to water depths of 10 ft MLLW (Ferguson and Wood, 1990, 1994). SRV are not known to occur seaward of the barrier islands in North Carolina. In sharp contrast, the maximum depth for SRV is 9 m off the northwest coast of Florida.

The presence or absence of aquatic beds and species of SRV are determined within an area equal to the minimum mapping unit and centered around the nominal station location. If SRV are present, visual observations of the number, size, and distribution of groups of plant shoots are recorded. These data are translated into an assessment of the presence or absence of an aquatic bed at the station considering the spatial distribution of SRV relative to the minimum detection and mapping units. The goal is to assess presence data in a manner relevant to photo interpretation (see "Photo interpretation of SRV"). Ancillary data recorded are water depth, salinity, water clarity, latitude and longitude, and descriptions of benthic sediment, algae, animals or animal shells, boulders, etc. A GPS position fix is taken to be differentially corrected (postprocessing) to a CEP of ±5 m. If the station data are not required to verify photo interpretation (see below), they can be used to estimate the accuracy of the habitat data (see "Recommended Accuracy Assessment Test").

Signature Verification and Supplemental Spatial Data

Locations selected from the photographs are observed during the same season and within one year of the photographic mission. The purpose of this survey is to resolve uncertainties in the photographs and, if necessary, to collect surface level data for inclusion in the spatial database. Surface level data intended to augment photo interpreted data require differentially corrected GPS positioning to a CEP of ±5 m.

Base Maps and Registration of Habitat Polygons

Accurate and up-to-date planimetric base maps of coastal land features are essential for georeferencing (establishing of geographic location) and scaling polygons of habitat interpreted from aerial photographs. C-CAP recommends 1) use of the most accurate and up-to-date base map available for the study area and 2) use of the most cost-effective technology to apply local horizontal control to interpreted data by registration of the photographs to base maps. The base map and the registration technology may vary regionally.

Planimetric Base Maps

The accuracy of the base map used for local horizontal control places a limit on the accuracy of the C-CAP product. The two base maps broadly available are NOAA shoreline and USGS 7.5' topographic maps. NOS produces highly accurate shoreline maps based on tide-coordinated and fully rectified photography (Swanson, 1949; Ellis, 1978; Slamma, 1980; NOAA Photogrammetry Branch, 1989; Crowell et al., 1991). When available and current, NOAA shoreline and coastal data should be used for C-CAP projects (e.g. Ferguson et al., 1991). These data, available in graphic and digital form, are products of the NOAA Coastal Mapping Program and are available from NOS. Shoreline data are produced from tide-coordinated photographic data and ground level survey data by the Photogrammetry Branch of NOS and meet or exceed national map accuracy standards. Horizontal ground control meets or exceeds third-order class I specifications found in the geodetic control standards (Federal Geodetic Control Committee, 1984). The Coastal Mapping Project of the Photogrammetry Branch provides data that depict the delineation of the mean high water line, the limit of emergent vegetation (apparent shoreline) and/or cultural shoreline, and in some areas, e.g. North Carolina, the approximate MLLW line. NOS shoreline data are a data source for NOAA nautical charts and USGS topographic maps. Coverage of the U.S. coastline is not complete, however, and for some areas the data may be dated.

In some locations, USGS 7.5' topographic maps may be the only base maps available at a scale of 1:24,000. These maps delineate the high tide line and cultural features and may meet C-CAP requirements. In many instances, however, these maps are out of date and temporal changes in shorelines may cause problems in the application of local horizontal control to compile the habitat polygons (Ferguson et al., 1989; Ferguson and Wood, 1990). This can reduce the positional and scaling accuracy of habitat data which is critical for change analysis (see "Recent Photography"). Care should be taken to determine the effective date of coastal features in these maps. Updates of these maps generally include cultural but not natural changes in shoreline. Coverage of the coastal United States is almost comprehensive, but dated. In some coastal areas, 1:24,000 scale orthophotoquads have been published as an alternative to topographic maps. Orthophotoquads at a scale of 1:24,000 are unsatisfactory for compilation from aerial photography in remote areas. Orthophotoquads do not have delineated shorelines, which may be needed when the preferred cultural features are insufficient to register the photograph to the map base.

Transfer of Polygons to the Map Coordinate Projection System

Polygons of habitat interpreted from aerial photographs are mapped into a standard map projection coordinate system. The UTM projection is recommended. C-CAP protocol allows the polygons interpreted from aerial photography to be transferred onto planimetrically accurate basemaps using three approaches:

1) Stereoscopically interpret the photographs and optically scale the polygons and photographic image to fit planimetric horizontal control in the basemap with a zoom transfer scope. This is the least expensive and often the most reliable approach. Habitat delineations drawn at the photographic scale through stereo viewing under magnification are transferred using camera lucida principles from the photographic overlay directly onto the planimetric basemap.

2) Process the aerial photographs into planimetrically accurate orthophotographs, and interpret and directly trace habitat polygons onto the planimetric base map. Interpretation of the orthophotographs is performed using monoscopic airphoto interpretation techniques. The orthophotographs must be at the same scale as the base map or the images must be enlarged or reduced to the map scale. This approach applies orthophotographic rectification (Thrower and Jensen, 1976), which corrects relief displacement in the original photographs and ensures planimetric mapping results in the database. Some loss of detail may occur since the orthophotography is a generation away from the original aerial photography. The process is expensive but accuracy is improved in areas with substantial vertical relief.

3) Delineate and simultaneously rectify and digitize habitat polygons by using an analytical stereo plotter. The three-dimensional stereo model of the aerial photographs is leveled and scaled in the analytical plotter (AP) and the interpreter views a three-dimensional landscape during photo interpretation. All polygonal interpretations are automatically stored in digital *x,y* coordinates in their proper planimetric position during photo interpretation (Welch et al., 1992), avoiding any error that might arise during information transfer in methods 1 and 2 discussed above. The polygon data are registered and digitized without the errors that are associated with transfer in a zoom transfer scope or by hand digitization. Unfortunately, analytical stereoplotters are expensive and their use requires special training. Some additional expense to locate *x, y,* and *z* control points may be necessary to successfully level the block of aerial photography. Recent advances in softcopy photogrammetry allow analytical stereoplotter functions to be accomplished using UNIX type workstations and image processing software (e.g. ERDAS ORTHO-max). Therefore, this alternative will become more affordable and attractive in the future.

An adaptation of the third approach is being tested by NOAA and the State of Florida. Photo interpretation is done as in approach 1. Registration and digitization of the interpreted habitat polygons is completed in the AP. Due to the high expense of AP and the specialization of AP technicians, this option may be feasible for processing data from SRV interpreters who do not have direct access to or training on an AP.

Digitization of Habitat Polygons

Habitat polygons that have been transferred to the planimetric base map according to procedure 1 or 2 above require digitization to be incorporated into the C-CAP spatial data base. Normally, digitization is accomplished using a digitizing tablet. Polygons are digitized with a digitizing table in point mode. The overlays are labeled according to the base map. Compilations are checked for clear delineation and cartographic acceptability of line work, existence of and consistency in feature attributes, and adequacy of horizontal control points. Compilations are checked along neat lines to confirm edgeline match and label match for polygons extending over adjoining maps. Any inconsistencies are brought to the attention of the map author.

Compilations are affixed to a digitizing table for georeferencing and data entry. The accuracy of the reference points, the four corners of the neat line, and no less than four internal tick marks on the overlays are checked to ensure that control points are within ±0.02 inches. This translates to ±40 ft or ±12.2 m from its stated location. If tolerance is exceeded on any one point, new control points are selected, digitized, and reevaluated until all points test within tolerance. Information regarding the georeferencing error for each control point is recorded on a documentation form. In addition the technician records other information about the overlay manuscript such as scale, size, media type, source map information, and author.

Polygons are digitized with the cartographic style and accuracy that is represented on the source manuscript. A technician performs digitizing and data processing to map completion, including matching edgelines, preparing initial check plots, and reviewing, editing, and preparing final check plots. All linework and labeling are reviewed using check plots produced at the source map scale. Each arc is checked for acceptance on a light table with the final check plot overlaid on the source map. Digitized linework should conceal original linework with exceptions for difference in line thickness, differences in media, and subtle differences of horizontal control on the source map and in digital files. Unacceptable data is flagged, edited, and reviewed prior to acceptance into the digital database. A data layer specification form is completed for formal documentation at the conclusion of all digitizing.

Scan digitizing may be an acceptable alternative to hand digitizing and could be applied at one of two stages: 1) when polygons are positioned on overlays of base maps or 2) when polygons are interpreted from individual photographs. Large format scanners would be required to scan an entire map, approximately 19 × 23 inch, in one pass. A standard desktop scanner, 8.5 × 11 inch, could scan the overlay from a single 9 × 9 inch photograph. In the latter case, geopositioning might be accomplished digitally without the use of the zoom transfer scope. In either case, the digital product would have to meet the same positional tolerances described above for data entered with the digitizing tablet.

Change Detection With Aerial Photographic Data

The C-CAP objective of site-specific change detection places greater emphasis on accuracy and precision of spatial data than required in one-time inventories or regional summaries of change. Methodology for monitoring site-specific change on a statewide or regional scale is a recent development (Ferguson and Wood, 1990; Orth et al., 1991; Ferguson et al., 1993). Quantitative historical data, with possible exceptions in Chesapeake Bay or spatially limited study sites, does not exist.

Recent Photography

C-CAP recommends post-classification change detection for SRV. Photographs taken in the same season of different years are independently interpreted, verified, and compiled to the base map. In this case independence does not mean different photo interpreters, compilers, and field personnel but rather an avoidance of side-by-side comparison of the data until after classification is complete. Postclassification change detection can be accomplished graphically, or polygons may be digitized and compared by using a geographic information system to detect spatial displacement and to quantify change. Although simple in concept, the statistics of change analysis are not well understood. Development of consensus for statistical evaluation of qualitative or spatial change is a subject of ongoing C-CAP research.

As an expedient to postclassification change detection, photographs from different years are compared directly or with mapped polygons. By using such comparisons, areas where change may have occurred can be identified rapidly but subjectively. Determining what constitutes significant change and how to objectively quantify the degree of change remain to be accomplished.

Historical Photography

The earliest metric-quality aerial photographs were acquired in about 1939. Prior to 1960, virtually all aerial photographs were black and white. Incomplete coverage, lack of coordination with tide, lack of camera calibration data, inappropriate scale, sun angle, and inappropriate time of year, or poor quality for visualization of benthic features often make these photographs unacceptable for a C-CAP change analysis. Interpretation of historical photographs is likely to proceed with limited or no concurrent surface level information for signature verification and should be attempted only by interpreters with extensive experience in the study area. Unless historical photography meets the C-CAP requirements listed in "Aerial Photography of SRV" and is supported by surface level data as discussed in "Field Surveys," the historical presence or absence of SRV at a given location may remain an open question. Some but not all SRV can be identified in less than optimal photography and be confirmed in the literature or in the memory of local residents. A visible signature for "bare bottom" or another nonhabitat signature is required to interpret absence of habitat at the time of photography. As a result, documentation of loss may be more likely than documentation of gain of SRV with historical photography.

Historical photographs may contain limited but valuable information on presence of submersed habitat other than SRV. Canopies of the giant kelp, *Macrocystis pyrifera*, for example, are readily discernible in color infrared (IR) photography because they have very high IR reflectance against a background of water that has no reflectance. The ease of photo interpretation of some macroalgae allows historical photography to be used to identify this and perhaps other types of habitat.

The most complete and general (but not comprehensive) source for historical photography is the Earth Resources Observation Systems (EROS) Data Center in Sioux Falls, South Dakota EROS records can be searched through the Earth Sciences Information Center (ESIC) of the USGS. The searcher must supply coordinates or the names of USGS 7.5' quadrangles that locate the area of interest. The ESIC office conducts a microfiche or computer-based search. Information produced includes latitude and longitude, emulsion, scale, month, year, source of the photography, cloud cover, camera, and frame numbers. Sources of this photography are USGS, National Aeronautics and Space Administration (NASA), USFWS, Agricultural Stabilization and Conservation Ser-

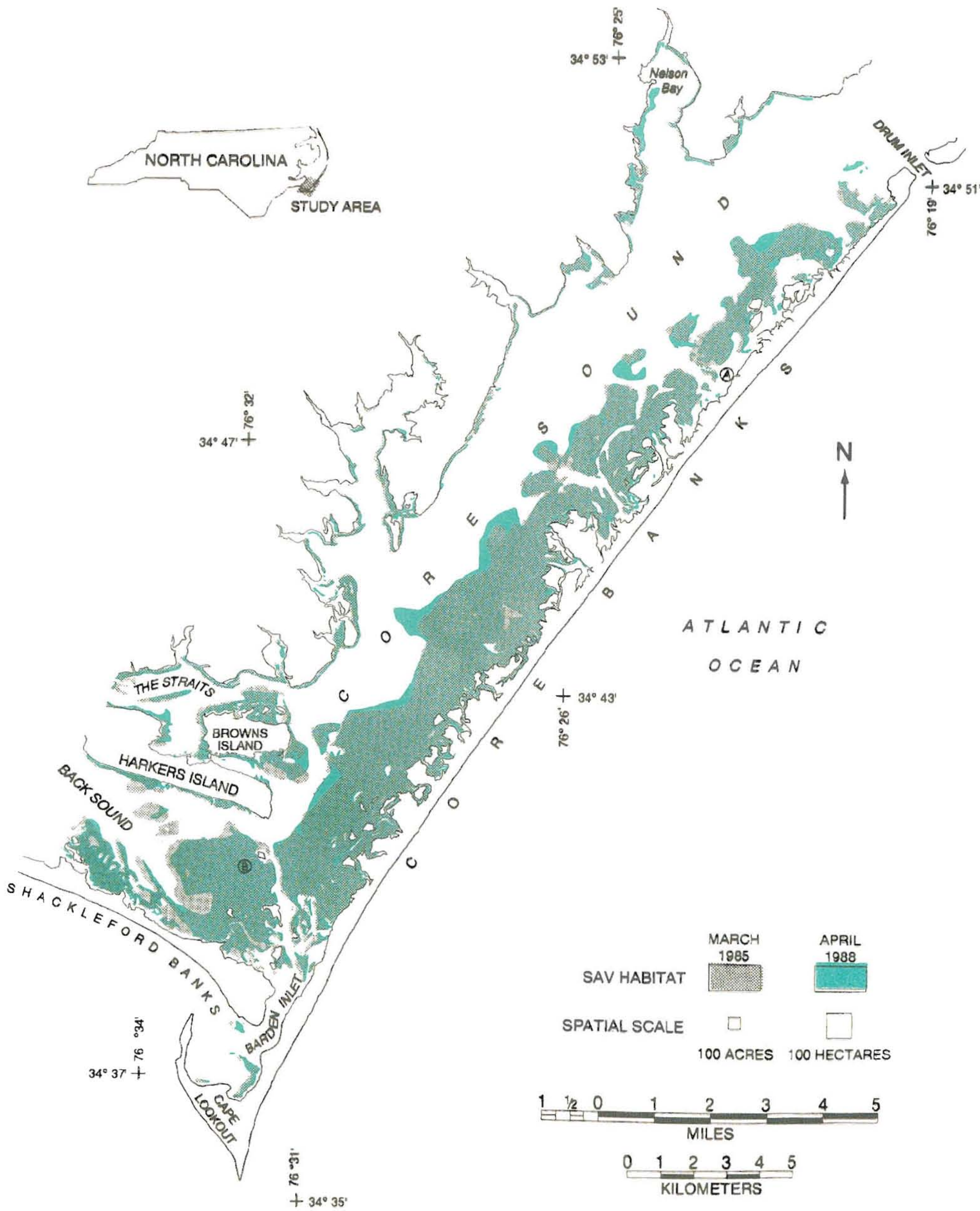


Figure 17

Seagrass habitat in Back Sound and southern Core Sound in 1985, gray, and in 1988, green. Pure gray indicates habitat present in 1985 but not in 1988. Light green indicates habitat in 1988 but not in 1985. The overlap of gray and green indicates the presence of habitat in both 1985 and 1988. (A) Head of the Hole, an area where seagrass habitat decreased due to mechanical harvesting of clams. (B) Spoil deposition island from which uncontained spoil was released into the water and buried seagrass habitat (Ferguson et al., 1992, 1993).

vice (ASCS), Soil Conservation Service (SCS), U.S. Forest Service (USFS), and some private companies. All historical photography identified in an ESIC search is reproducible. Substantial collections of historical photography may also be found in other Federal or State agencies, universities, or private companies. These collections of photography may be available for reproduction, distribution, loan, or examination. Federal sources include U.S. Army Corps of Engineers (COE), NOAA, National Archives for pre-1956 photos, and the Smithsonian Institution.

Change Detection of Seagrass Habitat in North Carolina

Ferguson et al. (1993) followed the C-CAP guidelines in Back Sound and southern Core Sound in North Carolina. That study demonstrated the feasibility of monitoring spatial change in SRV using C-CAP guidelines for large-scale metric aerial photography, photo interpretation, geographic positioning, and postclassification change detection techniques. Aerochrome MS 2448 color-reversal film was exposed in March 1985 at 1:20,000 and 1:12,000 scales. Aerocolor 2445 color-negative film was exposed at 1:24,000 scale in April 1988. All aerial photography was obtained by the NOS Photogrammetry Branch. The photography was coordinated with low tide and sun angle and was collected with minimal haze, no clouds below the aircraft, and no visible shadows from high clouds. Water was essentially free of white caps and clear enough for identification of vegetated and shallow unvegetated bottoms. Episodic wind, haze, local turbidity, and airborne pollen often precluded photography for one or more days. The sun angle during photography ranged from 15 to 30°. This sun angle localized sun glare to one edge of the photography while presenting illumination below the water surface. The aerial photographs were interpreted stereoscopically and the polygons were transferred to planimetric NOS shoreline maps with a zoom transfer scope. A graphical postclassification overlay approach was used to visually identify changes between years (Fig. 17). A gray tone in the chart indicates habitat present in 1985 but not in 1988. Light green indicates habitat in 1988 but not in 1985. The overlay of gray and green indicates the presence of seagrass habitat in both 1985 and 1988.

Summary statistics, obtained via automated geometric analysis of digitized video images of individual polygons (pixel size <0.03 ha) revealed that seagrass habitat is a major resource in the study area, comprising about 35% of the subtidal land. Total area of habitat changed less than 6%, from 7,030 ha in 1985 to 6,637 ha in 1988. Polygons along the mainland and Harkers Island tended to be linear and close to shore. Large broad areas of seagrass habitat were present in the subtidal shallows east of Browns Island, north of Shackleford Banks, and west of Core Banks. The total number of habitat polygons was similar in the two years, 151 in 1985 and 149 in 1988. Reliability of detected change was conducted by reinspection of the photography and is summarized in Ferguson et al. (1993). Some areas of detected change were confirmed by surface-level observations and two of these were associated with known anthropogenic disturbances. Some areas of detected change were confirmed but could not be associated with potential causes. Still others could not be confirmed, which may have been the result of variable quality in the photography. In a continuation of this study, the study area was rephotographed in 1992, selected polygons were mapped with GPS at surface level during the 1992 photographic window, and surface-level verification of signature was completed in 1993. Data for all three years, 1985, 1988, and 1992, will be digitized and change and positional accuracy will be assessed in a GIS.

Chapter 5
Spatial Data Quality Assurance and Control

Quality assurance and control (QA/QC) from data acquisition through final database compilation are the responsibility of each regional project team. Acceptance of the final database into the C-CAP archive and dissemination system are contingent upon the demonstration that the project has complied with the mandatory requirements stated in this document.

C-CAP standards of data quality are based on authoritative references (Goodchild and Kemp, 1990; Chrisman, 1991; Congalton, 1991; Lunetta et al., 1991; NIST, 1992). These documents recommend that producers of data document

- Lineage—A record of the type of data sources and the operations involved in the creation of a database.
- Positional accuracy and precision—The closeness of locational information (in *x,y* coordinates) to the true position.
- Attribute accuracy and precision—The closeness of attribute values to their true values.
- Logical consistency—The adherence of internal data structures to established conventions or stated rules.
- Completeness—The degree to which the data exhaust the universe of possible items.

C-CAP has added to this list

- Temporal accuracy and precision—The time over which source materials were acquired and observations were made.

Users are responsible for determining

- Fitness for use—The degree to which the data quality characteristics of each database and its components collectively suit an intended application.

The C-CAP protocol also distinguishes between

- Accuracy—The closeness of results, computations, or estimates to true values (or values accepted to be true), and
- Precision—The number of decimal places or significant digits in a measurement.

The accuracy of the resulting land-cover database for each time period and for change between time periods is a crucial measure of the success of C-CAP. Several different types of accuracy are involved, and some of them are difficult to measure. For rigorous statistical measures of accuracy, field-based reference data are exclusively preferred over other data sources, including aerial photographs.

Lineage

The sources, scales, or resolutions, and dates of materials involved in the preparation of all regional C-CAP databases must be documented (Lunetta et al., 1991), including

- satellite images or aerial photographs used in the analysis,
- aerial photographs (including oblique photographs) used as an aid in training or field verification if the photographs directly influenced the identification of land-cover types for significant portions of a given area,
- collateral information such as NWI data or soils maps if the information directly influenced the identification for significant portions of a given area,
- planimetric basemaps,
- state and county land-cover inventories or other surface level data, and
- sources and techniques of georeferencing, especially for submerged land and other land where identifiable features are sparse.

Positional Accuracy and Precision

Positional accuracy is concerned with the accuracy of the geometric placement of points, lines, and polygon boundaries. In land-cover databases, polygons are derived either from raster spectral data representing discrete pixels or from closed polygons delineating the edges of spectral signatures in photographs. In the first case, the placement of polygon boundaries depends on a) selection of spectral signatures for class boundaries and b) registration of pixel locations. The second case generally applies to C-CAP SRV projects in which the primary intent is to delineate limits between presence and absence of habitat classes. In this application, polygons of class 1 tend to occur as discrete objects in a large polygon of class 0 that has specified boundaries landward and unspecified boundaries seaward. In addition, one or more polygons of class 0 may be included within a polygon of class 1. The placement of polygon boundaries depends on a) limits of signatures attributed to the habitat class and b) registration of horizontal control points present in the base map and visible in the photography. In both cases, signature selection directly affects attribute distribution which, in turn, affects the size and shape of polygons. This effect is most common at polygon edges but may occur throughout the polygon, for example, as internal voids or as circumscribed polygons of different classes. The selection of spectral signatures for class boundaries is similar to the task of generalization that cartographers have traditionally faced in deciding where to draw boundaries between land-cover features.

For most remote-sensing applications, positional accuracy on the order of ±1–2 pixels has not been a major concern. Neither has positional accuracy for photographic delineations of submersed habitat been a major concern or a subject of independent verification. For a single time period, positional errors may not greatly affect the aggregate area of each land-cover type. Positional errors may be difficult to detect even when a specific polygon in the field is visited. For C-CAP, however, positional accuracy is a crucial concern (Ferguson et al., 1992 and 1993). The change database amounts to a comparison that will conspicuously record positional errors of one or more pixel dimensions in the satellite imagery and errors in excess of about 10 m in the photographic images used to delineate submersed habitat. This compounds the problem of recognizing real changes, which also tend to concentrate at polygon edges and class boundaries.

The registration of pixel locations is a purely geometric problem which has been greatly improved with recent advances in sensors, GPS, and image processing systems. Many vendors claim a positional accuracy of ±0.5 pixel root mean square error (RMSE) for commercial image processing systems and a CEP of 3–5 m for GPS. Selective availability (SA, the intentional distortion of GPS signals for military security purposes) reduces GPS precision to a CEP of 40 m when SA is in operation. Differential readings by multiple receivers can improve the quality of positional data, even when SA is active, to a CEP of <5 m. C-CAP regional analysts should verify vendor claims to their own satisfaction based on sources of higher precision. Unless stated otherwise, a geometric registration of ±0.5 pixel RMSE will be assumed for all C-CAP regional databases (±15 m if Landsat TM data are used).

For submerged land, the registration of polygon edges is a function of the metric quality of photographs, methods used to transfer the information to a planimetric map projection, and quality of the digitization performed. Positional accuracy is therefore subject to the accuracy of the base map including deviations not only between the source photography and the base map but also actual changes in the study area in the time between aerial photography for the base map and for the submersed habitat. A positional accuracy that meets national map accuracy standards is assumed for submersed habitat data. At the compilation scale of 1:24,000 this amounts to ±13.3 m on the ground, close to the ±15 meter precision of Landsat TM data for uplands and wetlands.

Generalization Versus Error

It is a tribute to the power of modern information technologies that what we used to call generalization, we now call error. With analog maps it has always been necessary to use human judgment in deciding, for example, precisely where a forest becomes a field. In reality most forests have some grass, and most fields have some trees or shrubs. In natural circumstances the boundary is not a precise line but rather a "fuzzy" zone of highly variable width in which the predominant land cover grades from one class to another. Scale and resolution are crucial determinants of such boundaries. In an analog map, scale limits the feasibility of drawing the densities and convolutions of lines that would be necessary to represent each patch of forest or each individual tree. Conceptually there will always be unrepresented boundaries because, in the modern sense of fractals, a nearly infinite number of convolutions are possible. Digital systems are capable of representing a much larger portion of all possible boundaries, but there are practical limitations affecting digital systems as well. In current technology the most often encountered limitation is the established resolution of satellite sensors.

While the terms "error" and "accuracy" are frequently used in regard to generalized boundaries, conceptually the "accurate" boundary can only be determined on the basis of a highly specific set of criteria that goes far beyond what can actually be implemented for large areas. Land-cover phenomena are prime examples of fuzzy sets. This fuzzy characteristic is explicitly recognized in the procedures of image processing (for example, the use of maximum-likelihood statistics), but the remote-sensing community traditionally has presumed that a "right" answer or "ground truth" can be determined if the analyst can get close enough to see the polygon and its boundary in the field or on the photograph. Yet different investigators "see" different land covers, a problem that is especially troublesome when the area is large enough to require multiple teams. In reality, land-cover phenomena are fuzzy sets whether viewed directly in the field or through remote sensors. Fuzziness persists because each class is defined, not by a discrete boundary, but by factors that grade from one class to another—spatially, temporally, categorically, and observationally. Also, classification and accuracy assessment procedures are not always implemented in a timely manner but often months or years after the image is collected or analyzed.

Generalization also occurs within delineated polygons whether derived from satellite or photographic images. In both cases a finite limit for signature detection and mapping exists. Minimum detection units are one pixel for spectral scanner data and about one meter for high altitude photographic images. Elimination of "salt and pepper" and preservation of reasonable accuracy for perimeter or areal estimates requires a minimum mapping unit of 4 pixels or about 0.4 ha. At a compilation scale of 1:24,000 the smallest polygon that can be traced from a photograph is about 20 m in diameter or an effective area on the ground of about 0.03 ha. Realistically, the goal for improving generalization should be to strive for consistency more than "accuracy."

Reference data for accuracy assessment must have a resolution and reliability that meet or exceed those of the C-CAP remotely sensed data. The reliability, including attribute and positional accuracy, must be demonstrated prior to its qualification as reference data for C-CAP. Reference data, including surface level observations, must be evaluated in accordance with C-CAP's minimum detection unit and minimum mapping unit for the remote data and with the classification system used to categorize the habitat. The presence of a characteristic species or natural or cultural feature may or may not, in itself, establish an area as a particular type of habitat. A number of questions need to be answered to conclude the appropriate category of land cover to assign based on the reference data: Does a characteristic species or feature meet the minimum detection unit of the remote sensor? What other characteristic species or features also are present within the minimum mapping unit? and What conclusion can be drawn from the reference data as to the C-CAP category for a given location based upon data generalized to the minimum detection and minimum mapping units?

Attribute Accuracy and Precision

Attribute accuracy is a measure of the probability that the land-cover type for any given polygon is properly identified according to the land-cover scheme. For example, the identification of a substantial polygon of "High-Intensity Developed" land as "Deciduous Woody Wetland" is a clear instance of categorical error. If 15% of all sample polygons for this class are misclassified as "Deciduous Woody Wetland" and other categories, the categorical accuracy for the "High-Intensity Developed" class is 85%. The remote-sensing literature is replete with procedures for measuring attribute accuracy (Congalton, 1991). Generally, these procedures serve well for current time periods and for relatively small study areas. Past time periods, however, cannot be field verified. Conventional procedures also are difficult to apply to large areas. Accuracy assessment of large change databases is currently infeasible due to the combination of past time period, large area, and the excessive number of "from" and "to" classes.

Logical Consistency

Tests for logical consistency should indicate that all row and column positions in the selected latitude/longitude window contain data. Conversion, integration, and registration with vector files should indicate that all positions are consistent with earth coordinates. Attribute files must be logically consistent. For example, when examining the change matrix for logical consistency, very few pixels should change from the urban category to any other category or from water to any category other than bare ground or marsh. The range of appropriate tests is left to the judgment and experience of regional analysts. All attribute classes should be mutually exclusive. The criteria cannot be met if land-use classes are included along with land-cover classes.

Completeness

The classification scheme should be comprehensive, containing all anticipated land covers. The C-CAP Coastal Land-Cover Classification System is intended to provide complete coverage, but regional analysts may find special land covers that are not included. It is the responsibility of regional project personnel to ensure that all categories are included and that all pixels are assigned a category. Regional analysts may use their discretion in deciding at what classification system level (0 to 3) they wish to classify. The level need not be the same for all branches of the classification scheme.

Temporal Accuracy and Precision

Regional analysts should document the time of data collection for the primary input data to at least the precision of year, day, and hour.

Fitness for Use

C-CAP workshops have involved many discussions with potential users and have devoted a great deal of effort to field verification and other types of verification.

C-CAP is confident that the databases resulting from compliance with this document will be of sufficient quality to support most policy and management activities as well as some regulatory, enforcement, and research activities. The spatial precision and attribute accuracy are not sufficient for enforcement of individual small permits, but they may be useful in evaluating cumulative impacts in the vicinity of a permit site or for evaluating individual sites larger than the minimum mapping unit. In the southeast region of the United States, a vast majority of the total area of coastal salt marsh or seagrass habitat that is potentially subject to direct loss, according to permits submitted, would be detectable in the C-CAP data (Rivera et al., 1992). Databases will also be of value in many applications, such as land-use planning, unrelated to the C-CAP mission. Ultimately, however, only the user can make the decision regarding fitness for use.

Recommended Accuracy Assessment Test

The recommended accuracy assessment for C-CAP regional databases is a test based on comparison with independent field samples. Independence should be guaranteed through the use of personnel who are not familiar with and do not have access to the results of the land-cover classification (Congalton, 1991).

Sample Selection and Field Mapping

Regional analysts are responsible for selecting unbiased, statistically meaningful area samples for field verification in the accuracy assessment process.

Accuracy Assessment for Individual Date Classification of Upland and Wetland Habitat Data

Accepted procedures in the remote-sensing, cartographic, and geographic literature assess 1) the positional accuracy of identifiable, stable features and 2) the categorical accuracy at the interior of class polygons. Unfortunately, the methods often neglect the fuzzy nature of land cover—categorically (e.g. the class boundary between grass and marsh), spatially (e.g. the polygon boundary between water and marsh), temporally, and observationally. Given these limitations, it is not feasible at this time to provide a quantitative estimate of accuracy with every C-CAP regional database. A reasonable alternative is to establish data quality objectives (DQO) designed to serve expected uses, establish and consistently implement a set of protocols and procedures, and manage the data production process to meet DQO's. C-CAP has conducted three workshops on accuracy assessment and sponsored two protocol development projects in the hope of devising new procedures that will work for accuracy assessment of large land-cover change databases.

Nevertheless, the following material identifies sound procedures that may be used to obtain unbiased field information which, in turn, may be statistically evaluated to perform an accuracy assessment for a single time period. This is a blind field test in which the field mapping personnel will not see the C-CAP Land-Cover and Land-Cover-Change Maps until all mapping has been completed.

Since the field mapping personnel may be unfamiliar with C-CAP, it is advised that they be required to submit a memorandum stating the design of the field mapping implementation. Early in the effort, regional analysts should review the design, in collaboration with NOAA, and reach agreement with the field mapping personnel regarding final implementation. Field personnel should be provided copies of the land-cover classification scheme and should be trained in its use.

The field personnel will be responsible for ensuring the positional accuracy and precision of each sample site and each land-cover class boundary within each site. Field personnel will be responsible for determining physical accessibility and obtaining permission for legal access to the sample sites.

An early determination will be made regarding who is responsible for acquiring the best available aerial photographs, topographic maps, and other collateral data to ensure an accurate mapping of each sample site for each time period. These materials will assist in mapping land cover and land-cover change for each site at 1:24,000 scale. Positional accuracy shall comply with national map accuracy standards. The determination of class type will be based primarily on field observation. The determination of class areas and boundaries will be based primarily on aerial photographs. The final results for each sample polygon will be provided in a digital form.

After completing field mapping, regional analysts will compare the generated map for each sample site with the C-CAP map for the same site. All discrepancies will be referred back to the field mapping personnel for a final check. The regional analyst may request a special examination and may accompany the field mapping personnel for a final reconciliation of any discrepancies for which field error is suspected.

The regional analysts will compile the results of all sample polygon comparisons and conduct a statistical analysis. The results of this analysis will be provided to the field mapping personnel for review and comment. At this point the field mapping personnel may also see the C-CAP land-cover and land-cover-change maps for the sample quadrangles.

The field mapping personnel will provide a brief documentation of the field mapping task for inclusion in the final accuracy assessment report to be prepared by the regional analysts. The field mapping personnel must be given an opportunity to comment on the results of the final statistical analysis if they so choose.

Accuracy Assessment for Individual Date Classification of Water and Submerged Land Data

Accuracy assessment for submersed habitat is similar to that for emergent and upland habitat but it should be noted that data for submersed habitat is intrinsically vector, not raster. Positional accuracy of polygon borders and attribute accuracy of a point location can both be assessed. Habitat polygons or areas of potential habitat should be stratified by class and region (water body) and randomly selected. Additional sample locations from potential habitat sites (i.e. sites of suitable depth but apparently devoid of habitat) should be randomly selected. Verification locations should be identified by latitude and longitude coordinates and visited in the field with GPS navigation. The nature of the habitat, if present, should be documented by inspection or sampling if necessary and the position of the sample or observation recorded to a CEP of <5 m. The entire perimeter of a small polygon or a section, e.g. 0.5 km of the perimeter of a large polygon, should be positioned by differentially corrected GPS at a point spacing of 3 to 20 m depending upon the degree of curvature in the perimeter. Differential GPS provides CEP of <5 m for single position fixes. C-CAP projects found that single point differential GPS position fixes did not exceed 10 m (Ferguson, R. L., J. A. Scope, and L. L. Wood, unpublished data). Habitats at the minimum mapping limit, i.e. with diameters on the order of 20 m, therefore, should be located and delineated with multiple position estimates. GPS manufacturers recommend collection of multiple position fixes for a time period of about 4 min to achieve CEP on the order of 1 or 2 m with differentially collected GPS. Multiple position fixes obtained at strategic points around the perimeter of the smallest mapped polygons would be required to ensure mapping the polygon rather than generating a scattered pattern of points.

Accuracy Assessment for Land-Cover Change Data

The methodological difficulties of accuracy assessment for the final change map are significantly greater than those for a single, current database. Remote-sensing, cartographic, and geographic literature provide no guidance on techniques for assessing the accuracy of a change detection map (Lunetta et al., 1991; Jensen and Narumalani, 1992). Even for a single-time database, existing procedures are ineffective for past land cover since the recommended "source of higher accuracy" cannot include actual field verification. Change detection databases compound the difficulty because they always include a past time period and a large number of "from" and "to" categories (potentially the square of the number of categories for each time). This large change matrix can make accuracy assessment more expensive than the original classification and change detection effort. Furthermore, if the distribution of error is thoroughly depicted by class and position, the accuracy database may be as large as the thematic database itself. Even worse, both the distribution of error and the distribution of actual change tend to concentrate on the same circumstances (for example, polygon edges and transitional classes, such as marsh and palustrine forest). C-CAP is sponsoring workshops to develop improved methods for assessing the accuracy of change databases and maps.

Comparison and Statistical Analysis

The C-CAP land-cover database and the field-mapped verification database should be compared and measured to determine differences in attributes for the base time period and for change that can be recognized in the field. The measures obtained from this comparison are numerical differences relating to the sample sites only. It will then be necessary to employ statistical algorithms to determine what the differences reveal about the accuracy of the entire regional database. These algorithms should be designed to estimate the attribute accuracy and positional accuracy of the change database. The necessary algorithms are not currently available in the remote-sensing, cartographic, and geographic literature (Congalton et al., 1991; Jensen and Narumalani, 1992). C-CAP funded two protocol development projects in an attempt to remedy this deficiency.

Chapter 6
Product Availability

Digital Product

Description and Availability

Regional databases generated by C-CAP participants will be provided to the C-CAP project director in accordance with procedures specified in research funding proposals (RFP), statements of work (SOW), funding documents, memoranda of understanding (MOU), or other applicable documents under which each regional project is authorized and conducted. The purpose of this transfer is to place each regional database into a central archive from which all data will be made available to the public. It will be the responsibility of the regional participants to document and certify that the data have been prepared in accordance with C-CAP protocols. C-CAP may conduct additional data quality and accuracy assessment tests before final submission to the archive. The data should adhere to the Spatial Data Transfer Standard (SDTS) proposed by the Federal Geographic Data Committee and adopted as a Federal Information Processing Standard (FIPS) (NIST, 1992). Commercial implementations are not currently available but will be marketed by software vendors in the near future. At a minimum, the standard should be considered a near-term goal with one or more de facto standards—such as DLG, ARC, DXF (geometry only), and ERDAS—accepted in the interim. Lineage, quality, and format information should be transmitted with the data disseminated to users.

The digital product for each region will be a change matrix of land cover by class for coastal submersed habitats, emergent coastal wetlands, and adjacent uplands. The only regional database currently completed and available to the public is the Chesapeake Bay Land-Cover Change Database for 1984 and 1988–89.

Digital products are available from

National Oceanographic Data Center (NODC)
1825 Connecticut Avenue, NW
Washington, DC 20235
(202) 606-4549

When more C-CAP regions have been completed, an on-line electronic catalog will be created for users to browse.

Digital Product Redistribution Restrictions—The product file will contain statements defining the responsibility of the user in regard to C-CAP data. The user must acknowledge NOAA as the source of the product whenever data are redistributed and must provide an accounting to NOAA stating who received copies of the database. If the redistributed data are modified, an accompanying disclaimer must acknowledge NOAA as the source of the original data, must state the nature of the modifications, and must relieve NOAA of responsibility for the modified data.

Liability Disclaimer—The user of C-CAP data will hold the U.S. Government and its agencies, officers, and employees harmless against any and all liability, including costs and expenses, which may result from or arise out of any use of the data.

Digital Product Format and Contents

The goal is to exchange the digital products in the Federal Spatial Data Transfer Standard (SDTS) format for raster data. Until the SDTS raster standard is available, the initial data products may not adhere to the final standard.

Product Identifiers and Characteristics—Each data transmittal from NODC to the user will be accompanied by documentation provided by the data producers stating the following:

- Geographical coverage in UTM coordinates
- UTM zone number
- Computer and operating systems used to create the file
- Precision of the computer system (e.g. 16-bit, 32-bit)
- Software used to create the file (e.g. ERDAS Imagine 8.2, ARC-Info 7.0)
- Type of file (ASCII, binary, ERDAS.IMG, ARC-Info coverage)
- Description and format of header file
- Data record format
- Number of classes
- Class names
- Number of pixels by class and by file, including the null class (i.e. no data in pixel)

The header file for each database will repeat the quantitative portion of this information.

Product Data Quality—The documentation will describe the lineage, date and source of data (i.e. instrument, and platform), resolution, positional accuracy and precision, attribute accuracy and precision, logical consistency, completeness, and temporal accuracy and precision of the data being transferred.

Guidance Version—The product file will contain a field indicating the "C-CAP Guidance for Regional Implementation" version used to produce the image product.

Transfer Verification Parameters—Each C-CAP product will contain unique verification parameters for the image raster data and a confirmation algorithm that can be applied to the image values. The algorithm tests whether the database received by the user is equivalent to the original. If an image has been damaged or modified, application of the algorithm will produce results different from the master values in the original data file maintained at the NODC. The occurrence of each class value (including the no data class) can be tabulated and compared with the original summary statistics.

Derived Data and Quality—The data product may include derived data, such as tabular summaries of land cover and accuracy assessments for specified areas (e.g. counties, watersheds, wildlife management areas). Data are defined as "derived data" if they cannot be used to reconstitute the C-CAP data at the pixel level.

Digital Data Values—The data values in raster format are numerical values representing the land-cover categories described in this document (see "The C-CAP Coastal Land-Cover Classification System"). A lookup table or other accompanying statement will define the relationship between the stored values and the land-cover categories.

Digital Product Medium

Digital data products are available on 9-track magnetic tapes and CD-ROM. As the completed coverage expands, these data may be available on other magnetic and optical media.

Digital Product Cost

The organization conducting each regional project will receive one copy of the final database as distributed by NODC at no cost. All other users will be charged the standard NODC reproduction fee.

Digital Product Ancillary Documentation

General Protocol—A copy of the "C-CAP Guidance for Regional Implementation" for the version used to produce the product will be available from the NODC in digital form for the cost of reproduction.

Specific Digital Products Documentation—Regional analysts may provide ancillary documentation for dissemination by NODC if both the documentation and the corresponding database are provided to NODC in a standard digital format.

Hardcopy Products

Upland and Wetland Habitats

Hardcopy maps of uplands and wetlands for selected areas will be produced for informational purposes, primarily to illustrate database content. At present there are no plans to publish hardcopy maps for general sale and distribution to the public. Requests for informational maps will be considered on a case-by-case basis.

Individuals and organizations should make their requests in writing to

Dr. Ford A Cross, Director
Beaufort Laboratory
NOAA/National Marine Fisheries Service
101 Pivers Island Road
Beaufort, NC 28516-9722

Organizations wishing to serve as value-added vendors of hardcopy products derived from C-CAP data should write to this address.

Submersed Habitats

Hardcopy maps are routinely produced as part of the submersed habitat change analysis because the techniques are currently based on aerial photographic interpretation in analog form. A limited number of publication-quality maps are reproduced at the completion of each regional task. Individuals and organizations may request copies on a "first come, first served" basis by writing to Dr. Ford A Cross at the address listed above.

Chapter 7
Users and Information Needs

Table 6 presents a matrix developed by participants in the regional concerns breakout group at the C-CAP Rhode Island Workshop (see Appendix 4). The matrix matches potential uses with C-CAP products and indicates the relative value of the product according to use. Interested parties are encouraged to modify this table from their own regional perspective and submit their modifications to C-CAP. This will enable C-CAP to generate matrices for each region or a single national matrix that will help ensure that C-CAP products meet the broadest range of user needs possible.

Table 6

The potential utility of C-CAP coastal land-cover information; abbreviations: H=high; M=moderate; L=low.

Potential uses	Map data	Digital data	Tables	Physical boundaries	Error estimation
Technical review	M	M	L	L	L
Decisions	M	M	L	L	L
Modeling	L	H	H	H	H
Interstate coordination	H	H	H	H	H
Enforcement	L	L	L	L	L
Hazard response	H	H	L	L	L
Policy	L	L	H	H	H
Management and planning	H	H	H	H	H
Education	H	H	M	M	H
Citizens	H	L	L	L	L
Commerce	H	H	L	L	H
Research	H	H	M	M	H

Chapter 8
Regional Participation

Purpose

NOAA C-CAP will endeavor to cooperate with all ongoing wetlands mapping and change-detection programs at the Federal, State, and regional levels. Priorities for NOAA funding allocation will be

1) biogeographic diversity,
2) joint funding efforts, and
3) existing field-based studies.

Other considerations will include:

1) areas of rapid development,
2) areas disturbed by major storms or other natural events, and
3) areas disturbed by hazardous technologies (e.g. oil spills).

Regional Project Summaries

St. Croix River Estuary (Border of Maine and New Brunswick, Canada)

This is a cooperative effort involving the U.S. Fish and Wildlife Service (USFWS), the Gulf of Maine Program, and Environment Canada. A change detection analysis was performed using TM imagery from 1985 and 1992. The image processing and change detection analysis was performed at Oak Ridge National Library (ORNL). Five field verification exercises were carried out in conjunction with USFWS personnel. The C-CAP change detection product has been completed and submitted to NODC.

Coastal Massachusetts

This is a cooperative submerged land effort involving the Massachusetts Department of Environmental Protection (DEP) Wetlands Conservancy Program. A pilot project focusing on training Massachusetts personnel in current SRV mapping techniques and adapting the C-CAP protocol for use in Massachusetts was conducted in the spring and summer of 1993. Photo interpretation and mapping are being performed by DEP personnel with technical assistance from the NMFS Beaufort Laboratory. The SRV polygons will be added to wetland data on coastal orthophoto maps.

Universities of Connecticut and Rhode Island

Faculty members of the Universities of Connecticut and Rhode Island worked cooperatively to examine several issues concerning coastal land-cover classification and change detection in the Northeast (Hurd et al., 1992). In the first part of the project, detailed GIS data on coastal wetlands in Rhode Island derived from aerial photography were used to establish coastal wetlands signatures for input to a digital classification of Landsat TM imagery. This work is crucial in assessing the extent to which an existing coastal wetlands dataset (e.g. NWI digital data) can be used to establish a classification for a larger TM dataset. Other areas of importance to C-CAP include assessments of 1) classification approaches best suited to characterize wetlands in southern New England; 2) techniques for monitoring coastal wetlands change in the Northeast using several change detection techniques to look at TM imagery from the same location for 1988 and 1982; and 3) multistate, multi-institutional collaboration in southern New England.

University of Delaware

University of Delaware faculty members at the Center for Remote Sensing played a lead role in developing the interagency land-cover classification system used by C-CAP (Klemas et al., 1993). The system was developed during joint meetings with representatives from key government agencies including NOAA, USGS, USEPA, USFWS, and COE.

Currently, University of Delaware faculty members are developing remote-sensing and field techniques for measuring indicators of wetland condition and functional health over large wetland areas. An overview of wetland health assessment techniques has been prepared, with special emphasis on wetland condition and functional health indicators that can be monitored with remote sensors (Patience and Klemas, 1993). The overview report contains a comprehensive literature search and chapters describing the techniques and their status. A joint study has been initiated with investigators from Louisiana State University and USEPA to work on impaired and healthy pilot test sites in Louisiana marshes. Field data, including measures of biomass, soils, hydrology, chemistry, biology, and light reflectance, are being correlated with Landsat TM imagery to assess biomass and stress indicators over large areas with the help of modified models and techniques developed during previous studies. The data derived from these investigations are crucial to C-CAP for early detection of functional change in habitat.

Oak Ridge National Laboratory

The C-CAP prototype and first regional project was conducted in the Chesapeake Bay region by ORNL (Dobson and Bright, 1991, 1992, and 1993). In the first phase, a land-cover classification was completed for a four-scene area using MSS data for 24–25 October 1978, and change detection was completed for portions of a scene in the vicinity of Metomkin Inlet, VA, using MSS data for 12 September 1974, MSS data for 24 October 1978, and TM data for 18 November 1982. The Virginia Institute of Marine Sciences (VIMS) was contracted to assist in field verification and training-sample identification. The results of this prototype served as a proof-of-principle for large-area change analysis, and the methods and techniques served as the basis for the draft protocol presented at the first protocol development workshop.

This initial prototype and proof-of-principle was conducted at the Oak Ridge Geographics Laboratory. All cartographic and geographic information processing was conducted by ORNL personnel using Oak Ridge Geographics software. Tentative land-cover classes were determined on the basis of supervised training samples in areas of known land cover. The tentative classes were checked with information available from other sources such as 1:24,000 USGS topographic maps and wetlands inventories (NWI and county marsh inventories). Investigators visited the area on 4–6 November 1985 for field verification of the tentative classes and for identification of additional training samples in the Wachapreague, Metomkin Inlet, and Saxis areas of Virginia. Land-cover classes were determined through iterative refinement of supervised training samples. Investigators visited the area in August 1986 for field verification of final land-cover classes in the York River estuary of Virginia and the Tangier Island and Blackwater National Wildlife Refuge areas of Maryland. Finally, the entire dataset was compared digitally on a cell-by-cell basis to land-cover data from the USGS Land Use Data Analysis (LUDA) database in order to resolve certain classes.

In the second phase, the change detection was extended to cover the full four-scene area by using TM data for 27 August 1984, 21 September 1984, 3 November 1988, and 10 October 1989. The final product consisted of a classified land-cover change matrix database for the entire Chesapeake Bay area. Regional maps at 1:500,000 scale and numerous local area maps covering individual USGS 1:100,000 and 1:24,000 quadrangle areas were prepared to illustrate static land cover for 1984 and 1988/1989 and land-cover change between these dates. The final database was delivered to NODC and is available on CD-ROM for purchase by the public. This analysis was conducted on graphics workstations employing ERDAS image processing software, ERDAS raster GIS software, and Oak Ridge Geographics GIS software. Processing and verification techniques were similar to those employed in the initial MSS/TM analysis. Investigators revisited the area in the spring and summer of 1991 and participated in the Maryland field verification workshop (See Appendix 4). Finally, the database was modified to accommodate the new C-CAP land-cover classification scheme and to incorporate suggestions and corrections resulting from the Maryland workshop. The protocols developed for the Chesapeake Bay project have been incorporated into the C-CAP protocols. Thus the final C-CAP Chesapeake Bay Land-Cover Change Database complies with this document.

Virginia Institute of Marine Sciences

The Virginia Institute of Marine Sciences has been conducting photographic mapping of submersed vegetation in the entire Chesapeake Bay beginning in 1978 and annually since 1984 (Orth et al., 1990 and 1991). Although not funded by C-CAP, this important work is considered a regional C-CAP project because of the voluntary collaboration among principal investigators. Methodology for the Chesapeake Bay project was a starting point for the C-CAP protocol. Data from Chesapeake Bay have been provided to C-CAP to attempt to overlay it with the land-cover data for Chesapeake Bay generated by ORNL. Historically, Chesapeake Bay has suffered a dramatic decline in SRV and associated fisheries. From 1984 to 1990, however, SRV habitat increased from 15,400 to 24,313 ha.

North Carolina State University

A land-cover classification project was conducted by the Computer Graphics Center at North Carolina State University (NCSU) prior to the University's involvement in C-CAP. Coincidentally, the four-scene area analyzed by NCSU was contiguous with the four-scene area analyzed by ORNL in the Chesapeake Bay project. Scene dates are contemporaneous with the 1988 Chesapeake Bay scenes. Faculty members of NCSU cooperated with ORNL research staff to investigate the potential for merging portions of these two independently conducted land-cover classifications based on TM digital data. The goal was to merge the project areas and form a seamless regional land-cover classification from the Chesapeake

Bay to Dare County, N.C. One of the major problems investigated was the development of a classification scheme adaptable to both areas. This research was a crucial test of the C-CAP concept of regional compatibility among neighboring databases developed by different organizations.

Beaufort Laboratory, National Marine Fisheries Service

The project in North Carolina is researching protocol for conducting and verifying change detection in SRV, including seagrasses and low-salinity-tolerant grasses and forbs. Simultaneously the project is completing the first comprehensive inventory of such habitat in North Carolina. The project was jointly funded by the Albemarle Pamlico Program of EPA's National Estuary Program.

Aerial photography to delineate SRV was first commissioned in 1985 (Bogue, Back, and southern Core Sounds). The rest of the aerial photography for all areas of potential SRV between Bogue Inlet and the Virginia border were taken between 1988 and 1992. All photography was subcontracted to the NOAA Photogrammetry Unit and acquired at scales of 1:12,000, 1:20,000, 1:24,000, or 1:50,000. The smallest scale photography provided a bridge between parallel flightlines (at 1:24,000) in eastern Pamlico Sound, where minor dimensions of some habitat areas exceeded 3 nmi.

All aerial photography from 1985 through 1991 was interpreted and most was compiled on base maps. The interpretation was supported by extensive systematic and directed sampling throughout the study area. At the time of photography, stations were selected by statified random sampling, visited, and sampled for species of submersed plants and ancillary data (sediment particle size and organic content, water depth, salinity, temperature, and Secchi depth and the presence of exposed peat deposits, shells, algae, or debris which might confuse signature identification). All locations of known and potential habitat, water <6 ft MLLW on nautical charts, were sampled by positioning a rectangular matrix of points over the nautical chart. Station positions approximately two scaled nautical miles apart were extracted from the chart and visited with the aid of LORAN C, now, preferably, GPS. After receipt and preliminary interpretation of the photographs, field surveys were conducted to verify the range of habitat signatures and confirm false signatures.

Photographs initially interpreted monoscopically are now interpreted stereoscopically. Polygons are traced on stable film at the photograph scale, rectified, and transferred to base maps with a zoom transfer scope. Base maps are NOAA shoreline manuscripts, if available, or USGS 7.5' topographic series maps, if consistent with current photographs, on stable media. The topographic maps are virtually complete for North Carolina (with the exception of Currituck Sound) but are out of date (mid-forties photography with occasional photo-revision for cultural features dated in the seventies or eighties). NOAA shoreline manuscripts are based on 1988 or more recent photography but are not complete for North Carolina. Necessary photographs for construction of manuscripts to complete shorelines in North Carolina were obtained by NOAA Photogrammetry Branch in 1988–92.

Habitat polygons were coordinate digitized by State of North Carolina personnel and incorporated into a statewide ARC-Info database referenced to the State Plane Coordinate System.

Three two-color charts of seagrass habitat at a scale of 1:36,000 and measuring about 3 × 4 ft were published and are available at no cost.

University of South Carolina

University of South Carolina faculty members performed a detailed investigation of the geographic area centered on two 7.5' U.S. Geological Survey quadrangles (quads) along South Carolina's coastal plain. These quads, representative of many other quads in coastal South Carolina, provide an opportunity to examine two very different wetland communities. One quad is directly on the coast and contains extensive *Spartina alterniflora* marsh, developed and undeveloped beach front, and a mature maritime forest. The other quad is 40 river miles inland and contains significant inland freshwater wetlands with extensive bottomland hardwoods. The project identified optimum parameters for conducting accurate coastal change detection including, but not limited to, 1) an optimum wetlands classification scheme; 2) an optimum type of remotely sensed data; 3) optimum digital image processing pattern recognition algorithms for C-CAP land-cover classification; 4) the applicability and utility of including ancillary data (e.g. NWI digital data) in the classification process; 5) optimum change detection algorithm logic; and 6) detailed error evaluation. Results were reported in Jensen et al. (1993a).

State of Florida, Department of Environmental Protection

State of Florida personnel are mapping submersed habitat in the Florida Keys, Florida Bay, Biscayne Bay, and Tampa Bay. Photography was conducted in the winter of 1991 and 1992 by the NOAA Photogrammetry Branch. The effort in the Keys is cooperative with NOAA's Marine Sanctuary Program. The Keys were photographed at 1:48,000 because of cost considerations and will demonstrate resolution of signatures of submersed habitat at a scale smaller than that acceptable with the current C-CAP protocol. The motion-compensating camera used in this case should enhance resolution. Photography in Florida Bay is being interpreted and ground verified in fiscal year 1993. C-CAP is partially funding the cost of photography and interpretation.

Texas Parks and Wildlife Department

This agency is currently processing TM imagery, as per the steps outlined in this document, for the entire Texas coast with technical assistance from ORNL. Two scenes in the Galveston Bay area for 2 December 1988 have already been classified, and a change detection analysis was performed, comparing a November 1992 scene with the southernmost of the 1988 scenes. Classification has been aided by an abundance of ground reference data as well as digital NWI data that are available for most of the Texas coast.

Columbia River, Tillamook Bay, and Willapa Bay (Oregon and Washington)

This is a cooperative effort involving cooperating agencies within the Columbia River Estuary Study Taskforce (CREST), NMFS's Point Adams Field Station, Hammond, Oreg., and Washington State personnel. Imagery for September 1989 and 1992 has been obtained and a change-detection analysis is being performed by CREST and its cooperators in conjunction with ORNL. Several field verification exercises have been performed, and a final change detection project is expected in fall 1994. This information should be useful to a variety of managers that are presently dealing with severely stressed salmon stocks throughout the study area.

The Hubbard Glacier and Russell Fjord, Alaska

This is a cooperative effort involving NMFS's Auke Bay Laboratory. A 1986 image is the only image available at this time that meets C-CAP cloud cover specifications. The implications of the future movements of the Hubbard Glacier make this project unique. During 1986 the Hubbard Glacier blocked off the mouth of the Russell Fjord and created the world's largest glacier-formed lake. Within months, rising water levels caused the glacier to burst, restoring tidal flow to the Fjord. Glacier experts predict that there is a 90% chance that the Hubbard Glacier will block off the mouth of the Russell Fjord again within the next 10 years. Because the portion of the glacier that will block off the Fjord is bigger than the one in 1986, it is predicted that the glacier will not burst. This would cause the rising waters to exit the Fiord at the end opposite the glacier, flowing into Old Situk Creek. This may significantly affect a very important salmon fishery, crucial to the inhabitants of nearby Yakutat, Alaska. C-CAP is presently looking for another image to perform a change analysis and provide more baseline information for future change-detection activities, should the glacier again close off Russell Fjord. The 1986 image has been processed by ORNL and the data has been submitted to NODC.

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Appendix 1

U.S. Geological Survey Land-Cover Classification Scheme for Remote Sensor Data

Appendix Table 1

Summary of Level I and Level II elements of the U.S. Geological Survey "Land Use and Land Cover Classification System for Use with Remote Sensor Data" (Anderson et al., 1976; USGS, 1992).

Level	Land-use and land-cover class
1	**Urban or Built-Up Land**
	11 Residential
	12 Commercial and Services
	13 Industrial
	14 Transportation, Communications, and Utilities
	15 Industrial and Commercial Complexes
	16 Mixed Urban or Built-up
	17 Other Urban or Built-up Land
2	**Agricultural Land**
	21 Cropland and Pasture
	22 Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas
	23 Confined Feeding Operations
	24 Other Agricultural Land
3	**Rangeland**
	31 Herbaceous Rangeland
	32 Shrub-Brushland Rangeland
	33 Mixed Rangeland
4	**Forest Land**
	41 Deciduous Forest Land
	42 Evergreen Forest Land
	43 Mixed Forest Land
5	**Water**
	51 Streams and Canals
	52 Lakes
	53 Reservoirs
	54 Bays and Estuaries
6	**Wetland**
	61 Forested Wetland
	61 Nonforested Wetland
7	**Barren Land**
	71 Dry Salt Flats
	72 Beaches
	73 Sandy Areas Other than Beaches
	74 Bare Exposed Rock
	75 Strip Mines, Quarries, and Gravel Pits
	76 Transitional Areas
	77 Mixed Barren Land
8	**Tundra**
	81 Shrub and Brush Tundra
	82 Herbaceous Tundra
	83 Bare Ground Tundra
	84 Wet Tundra
	85 Mixed Tundra
9	**Perennial Snow or Ice**
	91 Perennial Snowfields
	92 Glaciers

Appendix 2

U.S. Fish and Wildlife Service Wetland Classification Scheme

Appendix Table 2

Summary of the classification hierarchy of wetlands and deepwater habitats, showing systems, subsystems, and classes of the U.S. Fish and Wildlife Service "Classification of Wetlands and Deepwater Habitats of the United States" (Cowardin et al., 1979).

WETLANDS AND DEEPWATER HABITATS

System	Subsystem	Class
Marine	Subtidal	Rock Bottom
		Unconsolidated Bottom
		Aquatic Bed
		Reef
	Intertidal	Aquatic Bed
		Reef
		Rocky Shore
		Unconsolidated shore
Estuarine	Subtidal	Rock Bottom
		Unconsolidated Shore
		Aquatic Bed
		Reef
	Intertidal	Aquatic Bed
		Reef
		Streambed
		Rocky Shore
		Unconsolidated Shore
		Emergent Wetland
		Scrub-Shrub Wetland
		Forested Wetland
Riverine	Tidal	Rock Bottom
		Unconsolidated Bottom
		Aquatic Bed
		Streambed
		Rocky Shore
		Unconsolidated Shore
		Emergent Wetland
	Lower Perennial	Rock Bottom
		Unconsolidated Bottom
		Aquatic Bed
		Rocky Shore
		Unconsolidated Shore
		Emergent Wetland
	Upper Perennial	Rock Bottom
		Unconsolidated Bottom
		Aquatic Bed
		Rocky Shore
		Unconsolidated Shore
	Intermittent	Streambed
Lacustrine	Limnetic	Rock Bottom
		Unconsolidated Bottom
		Aquatic Bed
	Littoral	Rock Bottom
		Unconsolidated Bottom
		Aquatic Bed
		Rocky Shore
		Unconsolidated Shore
		Emergent Wetland
Palustrine		Rock Bottom
		Unconsolidated Bottom
		Aquatic Bed
		Unconsolidated Shore
		Moss-Lichen Wetland
		Emergent Wetland
		Scrub-Shrub Wetland
		Forested Wetland

Appendix 3
C-CAP Coastal Land-Cover Classification System Definitions

The C-CAP Coastal Land-Cover Classification System, described in Chapter 2 (Table 2), was developed to meet C-CAP requirements (Klemas et al., 1993). It is intended to be compatible with other classification systems to facilitate the exchange of data among related programs, especially USGS, NWI, and EPA's EMAP. Those classes underlined in Table 2 are of greatest importance to the C-CAP program and most can be detected by satellite sensors such as TM and SPOT.

Categories of the C-CAP Classification System

The system starts with three superclasses: 1.0-Uplands, 2.0-Wetlands, and 3.0-Water and Submerged Land. These superclasses are subdivided into classes and subclasses at the second and third levels, respectively. Most of the classes and subclasses in the C-CAP system are taken from Anderson et al. (1976), Cowardin et al. (1979), and USGS (1992). However, a few definitions have been modified to resolve conflicts between the Anderson et al. and Cowardin et al. categories, and some finer categories have been added (e.g. High-Intensity Developed Land and Low-Intensity Developed Land).

1.0-Upland

The superclass 1.0-Upland is divided into seven classes: 1.1-Developed Land, 1.2-Cultivated Land, 1.3-Grassland, 1.4-Woody Land, 1.5-Bare Land, 1.6-Tundra, and 1.7-Snow/Ice.

1.1-Developed Land

This class is composed of areas of intensive anthropogenic use. Much of the land is covered by structures and impervious surfaces. Anderson et al. (1976) called these areas "Urban or Built-up Land" although the definition clearly included suburban and rural areas:

> "Included in this category are cities; towns; villages; strip developments along highways; transportation, power, and communications facilities; and areas such as those occupied by mills, shopping centers, industrial and commercial complexes, and institutions that may, in some instances, be isolated from urban areas."

To clarify this apparent contradiction, C-CAP specifies all constructed surfaces regardless of land use. Developed Lands are divided into two Level II groups: 1.11-High Intensity and 1.12-Low Intensity.

1.11-High Intensity (Solid Cover)—High-Intensity Developed Land includes heavily built-up urban centers and large constructed surfaces in suburban and rural areas with a variety of different land uses. The High-Intensity category contains areas in which a significant land area is covered by concrete and asphalt or other constructed materials. Vegetation, if present, occupies <20% of the landscape. Examples of such areas include apartment buildings, skyscrapers, shopping centers, factories, industrial complexes, large barns, airport runways, and interstate highways.

1.12-Low Intensity (Mixed Pixels)—Low-Intensity Developed Land includes areas with a mixture of constructed materials (e.g. roofing, metal, concrete, asphalt) and vegetation or other cover. Constructed materials account for 50–79% of total area. These areas commonly include single-family housing areas, especially in suburban neighborhoods, but may include scattered surfaces associated with all types of land use. As the percentage of constructed material cover decreases, this category grades into Cultivated, Grassland, Woody, and other land-cover classes. A large building surrounded by several acres of grass, for example, might appear as one or more pixels of High-Intensity Developed Land, one or more pixels of Low-Intensity Developed Land, and many pixels of Grassland.

1.2-Cultivated Land

Agricultural Land in the Anderson et al. (1976) classification system was defined as

> ". . . land used primarily for production of food and fiber. On high-altitude imagery, the chief indications of agricultural activity will be distinctive geometric field and road patterns on the landscape and the traces produced by livestock or mechanized equipment."

C-CAP renamed this class "Cultivated Land" to emphasize land cover rather than land use. This category contains areas that have been planted, tilled, or harvested. Pastures and hayfields that are in a state of tilling or planting are also included. Otherwise, pasture or hayfield with well-established grasses are placed in the Grassland category (3.0). The Cultivated Land class is divided into three subclasses: 1.21-Orchards/Groves/Nurseries, 1.22-Vines/Bushes, and 1.23-Cropland.

1.21-Orchards/Groves/Nurseries—This category includes woody-stemmed crops that are dominated by single-stemmed, woody vegetation that is unbranched 0.6 to 0.9 m (2 to 3 ft) above the ground, having a height >3 m (10 ft). Some examples of the crops included are apple and cherry orchards, and palm date groves. Anderson et al. (1976) states

> "Orchards and groves produce the various fruits and nut crops. Tree nurseries that provide seedlings for plantation forestry also are included."

Isolated fruit trees and other orchards substantially smaller than the areal unit of observation are not included. Pine plantations are not included in this class; they are assigned to the Forest, Evergreen, Woody category (1.421).

1.22-Vines/Bushes—Vines/Bushes refers to areas of multiple stemmed, woody-stemmed crops that are shrubs <3 m (10 ft) in height. Examples of crops included in this category are blueberries, grapes, and other vines and bushes producing various fruit or nut crops (Anderson et al., 1976). This group has a different spectral signature than other Cultivated Land groups because of the size and spatial configuration of the vines, shrubs, and bushes.

1.23-Cropland—This class of Cultivated Land refers to any crop type that is planted on a regular basis. Crops may be planted annually in the same field year after year or on a rotating schedule. Anderson et al. (1976) states

> "The several components of Cropland now used for agricultural statistics include: cropland harvested, including bush fruits; cultivated summer-fallow and idle cropland, land on which crop failure occurs; and cropland in soil-improvement grasses and legumes."

C-CAP has modified this category to emphasize the instantaneous state of the land at the time of observation. Hence, for example, Cultivated Land in a five-year rotation scheme will be categorized as Cropland for the four years the land is tilled and as Grassland for the one year the land is fallow and covered by grasses. A fallow period of several years may result in a transition from Cropland to Grassland to Scrub/Shrub and back to Cropland.

Nurseries and horticultural areas (which include floriculture, seed, and sod areas) used perennially for those purposes are included in this category if woody-stemmed plants are not grown. Greenhouses normally fall in the Developed Land category.

1.3-Grassland

The Grassland category includes lands covered by natural and managed herbaceous cover. Historically, grassland has been defined as land where the potential natural vegetation is predominantly grasses, grasslike plants, and forbs, and where natural herbivory was an important influence in its pre-civilization state. Anderson et al. (1976) state

> "Some grasslands have been or may be seeded to introduce or domesticate plant species. The Grassland (Herbaceous) category contains both managed and unmanaged or natural herbaceous cover. The Grassland (Herbaceous) category can be found in every state in the United States along with Canada and Mexico."

The C-CAP category includes lands with herbaceous cover at the time of observation regardless of origin or potential. Pastures, hayfields, and natural rangelands are included. Also included are lawns and other managed grassy areas such as parks, cemeteries, golf courses, road rights-of-way, and other herbaceous-covered, landscaped areas. The Grassland class is divided into two subclasses: 1.31-Unmanaged and 1.32-Managed.

1.31-Unmanaged—The Unmanaged, Herbaceous, Grasslands category refers to herbaceous cover that is allowed to grow naturally and is not fertilized, cut, or tilled and planted regularly. This category includes, but is not limited to, the Anderson et al. (1976) "Herbaceous Rangeland" category:

> "the tall grass (or true prairie), short grass, bunch grass or palouse grass, and desert grass regions...Bunch grass and desert grass are found in many locations, representing transitional situations to desert shrub. Typical occurrences of grasslands include such species as the various bluestems (*Andropogon*), grama grasses (*Bouteloua*), wheatgrasses (*Agropyron*), needle-grasses (*Stipa*), and fescues (*Festuca*). This category also includes the palmetto prairie areas of south-central Florida, which consist mainly of dense stands of medium length and tall grasses such as wiregrass (*Aristida stricta*) and saw palmettos (*Seronoa ripens*), interspersed occasional palms (*Sabal palmetto*), and shrubs."

Unmanaged grasslands are found throughout the United States, often as a transitional phase in the regrowth of abandoned Cropland, clearcut Woody Land, or land affected by natural disturbance.

1.32-Managed—These grasslands are maintained by human activity and include lawns, golf courses, pastures, hayfields, and other areas of grassland in which seeding, fertilization, or irrigation enhance biomass productivity. This category may contain vegetation that grows as fallow if vigorous growth persists due to the residual effects of management practices in the nonfallow state.

1.4-Woody Land

The Woody Land class includes any species with an aerial stem that persists for more than one season. The class is divided into three subclasses: 1.41-Deciduous, 1.42-Evergreen, and 1.43-Mixed.

1.41-Deciduous—The Deciduous Woody subclass includes all forest and shrub areas having a predominance of trees and shrubs that lose their leaves or needles at the end of the frost-free season or at the beginning of a dry season. Areas in this category are composed of greater than two-thirds deciduous trees and shrubs. The Deciduous Woody category can be divided into two groups: 1.411-Forest and 1.412-Scrub/Shrub.

1.411-Forest—Deciduous Forest includes areas dominated by single stemmed, woody vegetation unbranched 2–3 ft above the ground having a height ≥6 m (20 ft). Forest Deciduous Woody areas have a tree-crown areal density (crown closure percentage) of ≥10 percent, are stocked with trees capable of producing timber or other wood products, and exert an influence on the climate or water regime. In most parts of the United States, these would be the hardwoods such as oak, *Quercus*, maple, *Acer*, or hickory, *Carya*, and the "soft" hardwoods, such as aspen, *Populus tremuloides*. Tropical hardwoods are included in the Evergreen Forest (Woody Land) category (1.421). Deciduous forest types characteristic of Wetland, such as tupelo, *Nyssa*, or cottonwoods, *Populus deltoides*, are not included in this category.

1.412-Scrub/Shrub—Deciduous Scrub/Shrub includes all areas having a predominance of shrub that lose their leaves or needles at the end of the frost-free season or at the beginning of the dry season (Anderson et al., 1976). This category contains vegetation that is <6 m (20 ft) in height. The species include true shrubs, young trees, and trees or shrubs that are small or stunted because of environmental conditions. True shrubs are those woody-stemmed species that exhibit several erect, spreading, or prostrate stems and a general bushy appearance. Shrub Lands may represent a successional stage leading to forests or they may be relatively stable communities. Forest regrowth composed of young trees <6 m tall is also included in this category.

1.42-Evergreen—The Evergreen Woody subclass contains forests and shrubs that do not lose their leaves or needles at the end of a frost-free season or at the beginning of a dry season. The Evergreen Woody category is subdivided into two additional categories: 1.421-Forest and 1.422-Scrub/Shrub.

1.421-Forest—Evergreen Forest includes areas in which ≥67% of the trees remain green throughout the year. Both coniferous and broad-leaved evergreens are included in this category. Coniferous evergreens predominate except in tropical regions where broad-leaved evergreens are indigenous. Coniferous evergreens, often called softwoods, include such eastern species as the longleaf pine, *Pinus palustris*, slash pine, *P. ellioti*, shortleaf pine, *P. echinata*, loblolly pine, *P. taeda*, and other southern yellow pines; various spruces, *Picea*, and balsam fir, *Abies balsamea*; white pine, *P. strobus*, red pine, *P. resinosa*, and jack pine, *P. banksiana*; and hemlock, *Tsuga canadensis*; and such western species as Douglas fir, *Pseudotsuga menziesii*, redwood, *Sequoia sempervirens*, ponderosa pine, *P. monticola*, Sitka spruce, *P. sitchensis*, Engelmann spruce, *P. engelmanni*, western redcedar, *Thuja plicata*, and western hemlock, *Tsuga heterophylla*. Evergreen species commonly associated with Wetland, such as tamarack, *Larix laricina*, or black spruce, *P. mariana*, are not included in this category.

1.422-Scrub/Shrub—Evergreen Scrub/Shrub includes areas in which ≥67% of the shrubs remain green throughout the year. Anderson et al. (1976) states

> "Both coniferous and broad-leaved evergreens are included in this category. The typical Shrub Lands are found in those arid and semiarid regions characterized by such xerophytic vegetative types with woody stems as big sagebrush, *Artemisia tridentata*, shadscale, *Atriplex confertifolia*, greasewood, *Sarcobatus vermiculatus*, and creosotebush, *Larrea divaricata*. When bottom lands and moist flats are characterized by dense stands of typical wetland species...they are considered Wetland. Where highly alkaline soils are present, halophytes such as desert saltbush, *Atriplex* may occur. The type, density, and association of these various species are useful as indicators of the local hydrologic and pedologic environments. Also included in this category is chaparral, a dense mixture of broadleaf evergreen sclerophyll shrubs, and the occurrences of mountain mahogany, *Cercocarpus ledifolius* and scrub oaks, *Quercus*."

1.43-Mixed—The Mixed Woody class includes all forest and shrub areas where both evergreen and deciduous trees and shrubs grow and neither predominates. When evergreen and deciduous species each respectively occupy ≥33 % of an area, the land is classified as Mixed Woody. The Mixed Woody category is subdivided into two additional categories: 1.431-Forest and 1.432-Scrub/Shrub.

1.431 Forest—This class includes all forested areas where both evergreen and deciduous trees are growing and neither predominate.

1.432 Scrub/Shrub—This class includes all shrub areas where both evergreen and deciduous shrubs are growing and neither predominate.

1.5-Bare Land

The Bare Land class, modified from "Barren Land" in Anderson et al. (1976) is composed of bare rock, sand, silt, gravel, or other earthen material with little or no vegetation regardless of its inherent ability to support life. Vegetation, if present, is more widely spaced and scrubby than that in the vegetated categories. Unusual conditions, such as a heavy rainfall, occasionally may result in a short-lived, luxuriant plant cover. Wet, nonvegetated exposed lands are included in the wetland categories.

Categories of Bare Land include Dry Salt Flats; Beaches; Sandy Areas other than Beaches; Bare Exposed Rock; Strip Mines, Quarries; Gravel Pits; Transitional Areas; and Mixed Barren Land:

Dry Salt Flats are level bottoms of interior desert basins that capture infrequent rainfall and do not qualify as Wetland. Salt concentrations result in highly reflective surfaces.

Beaches are the smooth sloping accumulations of sand and gravel along shorelines. The inland face is usually stable, but the shoreward face is subject to erosion by wind and water and subject to deposition in protected areas.

Sandy Areas other than Beaches are composed primarily of dunes—accumulations of sand transported by the wind. Sand accumulations most commonly are found in deserts although they also occur on coastal plains, river flood plains, and deltas and in periglacial environments. When such sand accumulations are encountered in tundra areas, they are not included here but are placed in the Bare Ground Tundra category.

Bare Exposed Rock includes areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, and other accumulations of rock without vegetative cover, with the exception of such rock exposures in tundra regions.

Strip Mines, Quarries, and Gravel Pits are areas of extractive mining activities with significant surface expression. Vegetative cover and overburden are removed to expose such deposits as coal, iron ore, limestone, and copper. Quarrying of building and decorative stone and recovery of sand and gravel deposits also result in large open-surface pits. Active, inactive, and unreclaimed strip mines, quarries, borrow pits, and gravel pits are included in this category until other cover has been established, after which the land is classified in accordance with the resulting cover. Unused pits or quarries that have been flooded, however, are placed in the appropriate Water category.

Transitional Areas are dynamically changing from one land cover to another, often because of land use activities. This transitional phase occurs when, for example, forest lands are cleared for agriculture and wetlands are drained for development. Often land becomes temporarily bare as construction initiates the transition from Woody Land or Grassland to a future cover associated with residential, commercial, or other intensive land use. Lands, such as spoil banks and sanitary landfills, that are temporarily altered by grading and filling are considered transitional.

1.6-Tundra

Tundra is the term applied to the treeless cover beyond the latitudinal limit of the boreal forest in poleward regions and above the elevation range of the boreal forest in high mountains. In the United States, tundra is found primarily in Alaska, several areas of the western high mountain ranges, and isolated enclaves in the high mountains of New England and northern New York.

The vegetative cover of the tundra is low and dwarfed, often forming a continuous mat. Plant characteristics are an adaptation to an extreme physical environment in which temperatures may average above freezing only one or two months of each year, strong desiccating winds may occur, great variation exists in solar energy, and permafrost is ubiquitous beneath the surface.

The number of species in the flora is relatively small compared with typical middle- and low-latitude flora, and the number decreases as the environment becomes more severe with increasing latitude and elevation. The tundra vegetation is most luxuriant near the boreal forest. Conversely, plant density and species diversity are lowest near the boundaries of permanent ice and snow areas, where only isolated patches of vegetation occur on generally bare surfaces.

Tundra may be further subdivided into Shrub and Brush Tundra, Herbaceous Tundra, Bare Ground Tundra, Wet Tundra, and Mixed Tundra (Anderson et al., 1976).

1.7-Snow/Ice

The temporal dimension is crucial in determining snow and ice cover. Any snowfall, for example, deep enough to conceal another land cover, no matter how briefly, comprises the visible surface at that time and technically constitutes the land cover for the period of its duration. As a practical matter, of course, analysts usually need to characterize the land cover persisting for a greater portion of the year. At higher latitudes and elevations, snow and ice persist for greater portions of the year, and seasonal coverage becomes a more important concern. At extreme latitudes and elevations, Perennial Snow/Ice cover is of paramount interest. A combination of environmental factors may cause snow and ice to survive the summer melting season. Areas of Perennial Snow/Ice cover are defined as those where snow, firn (coarse, compacted granular snow), or ice accumulation exceeds ablation. Ablation is the combined loss of snow or ice mass by evaporation and meltwater run-off (Anderson et al., 1976). The class Snow/Ice contains two subclasses: 1.71-Perennial Snow/Ice and 1.72-Glacier.

1.71-Perennial Snow/Ice—This class contains areas covered year-round with snow and ice but which have not accumulated sufficient ice to be considered Glaciers. Snowfields can be extensive and thus representative of a regional climate, or can be isolated and localized, where they are known by various terms, such as snowbanks. The regional snowline is controlled by general climatic conditions and closely parallels the regional 32° F (0° C) isotherm for the average temperature of the warmest summer month. The use of the term "line" is somewhat misleading because the "snowline" represents an irregular transitional boundary, which is determined at any single location by the combination of snow accumulation, snow melt, and ablation, variables that can change rapidly within short distances because of changes in local topography and slope orientation. Snowfields normally can be distinguished from the following Glacier subclass by their relative lack of flow features (Anderson et al., 1976).

1.72-Glaciers—Glacial ice originates from the compaction of snow into firn and finally into ice under the weight of several successive annual accumulations. Refrozen melt water usually contributes to the increasing density of the glacial ice mass. With sufficient thickness, weight, and bulk, flow begins; all glaciers exhibit evidence of present or past motion in the form of moraines, crevasses, and other glacial geomorphic features.

Where the snowline of adjacent ice-free areas extends across the glacier, it is known as the firn limit, which represents the dividing line between the glacier's two major zones, the zone of accumulation and the zone of ablation. While glaciers normally are recognized easily, certain glacial boundaries may be subject to misinterpretation, even by the experienced interpreter. Flow features up-glacier from the firn limit typically are obscured by fresh snow, forcing the image interpreter to depend on secondary information, such as valley shapes, or to seek a more discriminating sensor. Similarly, glacial drift materials (rock and soil) may stripe the surface of a glacier, and moraine material may cover the terminus (or snout) because of ablation, making boundary determination in that vicinity difficult. This later problem occasionally is compounded by the presence of considerable vegetation rooted in the insulating blanket of ablation moraine (Anderson et al., 1976).

2.0-Wetland

Cowardin et al. (1979) define wetlands as lands where saturation with water is the dominant factor determining soil development and the types of plant and animal communities living in the soil and on its surface. The single feature that all wetlands share is soil or substrate that is at least periodically saturated with or covered by water. The upland limit for vegetated wetlands with soil is 1) the boundary between land with predominantly hydrophytic cover and land with predominantly mesophytic or xerophytic cover; 2) for nonvegetated wetlands with soil, the boundary between soil that is predominantly hydric and soil that is predominantly nonhydric; or 3) in the case of wetlands without vegetation or soil, the boundary between land that is flooded or saturated sometime during the growing season each year and land that is not. Most wetlands are vegetated and are found on soil.

In the C-CAP Coastal Land-Cover Classification System (Table 2), "Wetland" includes all areas considered wetland by Cowardin et al. (1979) except for Wetland Bottoms, Aquatic Beds, and Nonpersistent Emergent Wetlands. Subdivision of the Wetlands class closely resembles the Cowardin et al. system (Appendix 2). At Level II, C-CAP uses certain Cowardin et al. classes (e.g. Rocky Shore, Unconsolidated Shore, Emergent Wetland) or grouped Cowardin et al. classes (e.g. Woody Wetland = Scrub-Shrub + Forested Wetland) in combination with Cowardin et al. systems (i.e. Marine, Estuarine, Riverine, Lacustrine, Palustrine). Thus, C-CAP Level II wetland classes became 2.1-Marine/Estuarine Rocky Shore, 2.2-Marine/Estuarine Unconsolidated Shore, 2.3-Marine/Estuarine Emergent Wetland, 2.4-Estuarine Woody Wetland, 2.5-Riverine Unconsolidated Shore, 2.6-Lacustrine Unconsolidated Shore, 2.7-Palustrine Unconsolidated Shore, 2.8-Palustrine Emergent Wetland (persistent), and 2.9-Palustrine Woody Wetland.

Salinity displays a horizontal gradient in marshes typical of coastal plain estuaries. This is evident not only through the direct measurement of salinity but also in the horizontal distribution of marsh plants in marshes with positive correlations between vertical rise and landward location (Daiber, 1986). Therefore Marine Estuarine Emergent Wetland was partitioned into Haline (Salt) and Mixohaline (Brackish) Marshes. For both subclasses, the definitions used in Cowardin et al. (1979) were used, i.e. the salinities for Mixohaline range from 0.5 to 30 ppt, and Haline include salinities >30 ppt. Within a marsh, plant zonation is usually quite evident. Along the Atlantic coast of North America the pioneer plant is saltmarsh cordgrass, *Spartina alterniflora*, which often appears in pure stands. Higher up the slope saltmeadow hay, *Spartina patens*, becomes dominant, while the upland edges are bordered by marsh elder, *Iva frutescens*, and groundsell tree, *Baccharis halimifolia*. Thus, salt marshes could be subdivided further into High Marsh and Low Marsh.

C-CAP does not attempt to identify Nonpersistent Emergent Wetlands, because they are seasonal. These wetlands are classified as "Riverine Water" and "Lacustrine Water." Marine and Estuarine Rocky Shores were combined into a single class, Marine/Estuarine Rocky Shore. The same logic was applied to create Marine and Estuarine Unconsolidated Shores, Aquatic Beds, and Water.

3.0-Water and Submerged Land

All areas of open water with <30% cover of trees, shrubs, persistent emergent plants, emergent mosses, lichens, or other land cover are grouped under the heading, Water and Submerged Land, regardless of whether the area is considered wetland or deepwater habitat under the Cowardin et al. (1979) classification system. The Level II C-CAP Water and Submerged Land classes are modified from Cowardin et al. (1979) (Appendix 2), and include Water, Reef, and Aquatic Beds. Marine and Estuarine Reefs and Marine and Estuarine Aquatic Beds are combined into two classes, 3.2-Marine/Estuarine Reef and 3.3-Marine/Estuarine Aquatic Bed. Aquatic bed in rivers, lakes, and streams are assigned to 3.4-Riverine Aquatic Bed, 3.5-Lacustrine Aquatic Bed, and 3.6-Palustrine Aquatic Bed classes. This last class also includes Cowardin et al.'s (1979) Rock Bottom and Unconsolidated Bottoms.

Most C-CAP products will designate water as a single class (3.1) regardless of system type. It is recognized, however, that the major systems (Marine/Estuarine, Riverine, Lacustrine, Palustrine) are ecologically quite different from one another. Hence, the four systems at Level III are shown as subclasses: 3.11-Marine/Estuarine, 3.12-Riverine, 3.13-Lacustrine, and 3.14-Palustrine. Even though C-CAP does not commit itself to provide the subclass data, this option is encouraged for regional participants. Incorporating water system information makes the C-CAP scheme more compatible with the Cowardin et al. system. The subclass 3.11-Marine/Estuarine includes bottoms and undetected reefs and aquatic beds. The subclasses 3.12-Riverine, 3.13-Lacustrine, and 3.14-Palustrine include bottoms and undetected aquatic beds or non-persistent emergent wetlands.

3.3-Marine/Estuarine Aquatic Beds includes the subclass Rooted Vascular, which is broken into High Salinity (>5 ppt) and Low Salinity (<5 ppt). The break was made at 5 ppt salinity because it separates true seagrasses that require high salinity from low salinity species that are tolerant of or require fresh water. Both low and high salinity types of SRV are important to the C-CAP project. High Salinity includes Cowardin et al.'s mesohaline, polyhaline, euhaline, and hyperhaline salinity categories. Low Salinity includes Cowardin et al.'s oligohaline and fresh categories.

Systems and Classes of Cowardin et al.

Most of the C-CAP wetland and water definitions are taken directly from Cowardin et al. (1979). This classification is hierarchical, progressing from systems and subsystems, at the most general level, to classes, subclasses, and dominance types. Appendix Table 2 illustrates the hierarchical structure to the class level. Modifiers for water regime, water chemistry, and soils are applied to classes, subclasses, and dominance types. Special modifiers describe wetlands and deepwater habitats that have been either created or highly modified by human or beaver activity.

Systems

The term system refers to a complex of wetlands and deepwater habitats that share the influence of similar hydrologic, geomorphologic, chemical, or biological factors. Systems are subdivided into subsystems.

The characteristics of the five major systems—Marine, Estuarine, Riverine, Lacustrine, and Palustrine—have been discussed at length in the scientific literature and the concepts are well recognized. However, there is disagreement as to which attributes should be used to bound the systems in space. For example, both the limit of tidal influence and the limit of ocean-derived salinity have been proposed as definitions of the upstream limit of Estuarine Systems (Caspers, 1967). As Bormann and Likens (1969) affirm, boundaries of ecosystems are defined to meet practical needs.

Marine System

Definition. The Marine system consists of the open ocean overlying the continental shelf and its associated high-energy coastline. Marine habitats are exposed to the waves and currents of the open ocean, and the water regimes are determined primarily by the ebb and flow of ocean tides. Salinities exceed 30%, with little or no dilution except near the mouths of estuaries. Shallow coastal indentations or bays without appreciable freshwater inflow, and coasts with exposed rocky islands that provide the mainland with little or no shelter from wind and waves, are also considered part of the Marine System because they generally support typical marine biota.

Limits. The Marine System extends from the outer edge of the continental shelf shoreward to one of three lines: 1) the landward limit of tidal inundation (extreme high water of spring tides), including the splash zone from breaking waves; 2) the seaward limit of wetland emergents, trees, or shrubs; or 3) the seaward limit of the Estuarine System, where this limit is determined by factors other than vegetation. Deepwater habitats lying beyond the seaward limit of the Marine System are outside the scope of this classification system.

Estuarine System

Definition. The Estuarine system consists of deepwater tidal habitats and adjacent tidal wetlands that are usually semi-enclosed by land but have open, partly obstructed, or sporadic access to the open ocean, and in which ocean water is at least occasionally diluted by freshwater runoff from the land. The salinity may be periodically increased above that of the open ocean by evaporation. Along some low-energy coastlines there is appreciable dilution of sea water. Offshore areas with typical estuarine plants and animals, such as red mangroves, *Rhizophora mangle*, and eastern oysters, *Crassostrea virginica*, are also included in the Estuarine system.

Limits. The Estuarine system extends 1) upstream and landward to where ocean-derived salts measure <0.5% during the period of average annual low flow; 2) to an imaginary line closing the mouth of a river, bay, or sound; and 3) to the seaward limit of wetland emergents, shrubs, or trees where they extend beyond the river mouth defined by (2). The Estuarine System also includes offshore areas of continuously diluted sea water.

Riverine System

Definition. The Riverine system includes all wetlands and deepwater habitats contained within a channel, except 1) wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens and 2) habitats with water containing ocean-derived salts >0.5%. A channel is "an open conduit either naturally or artificially created which periodically or continuously contains moving water, or which forms a connecting link between two bodies of standing water."

Limits. The Riverine System is bounded on the landward side by upland, by the channel bank (including natural and man-made levees), or by wetland dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens. In braided streams, the system is bounded by the banks forming the outer limits of the depression within which the braiding occurs.

The Riverine System terminates downstream where the concentration of ocean-derived salts in the water exceeds 0.5% during the period of annual average low flow, or where the channel enters a lake. It terminates upstream where tributary streams originate or where the channel originates from a lake. Springs discharging into a channel are considered part of the Riverine System.

Lacustrine System

Definition. The Lacustrine System includes wetlands and deepwater habitats with all of the following characteristics: 1) situated in a topographic depression or a dammed river channel; 2) lacking trees, shrubs, persistent emergents, emergent mosses or lichens with >30% areal coverage; and 3) total area >8 ha (20 acres). Similar wetland and deepwater habitats totaling less than 8 ha are also included in the Lacustrine system if an active wave-formed or bedrock shoreline feature makes up all or part of the boundary, or if the water depth in the deepest part of the basin is >2 m (6.6 feet) at low water. Lacustrine waters may be tidal or nontidal, but ocean-derived salinity is always <0.5%.

Limits. The Lacustrine System is bounded by upland or by wetland dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens. Lacustrine systems formed by damming a river channel are bounded by a contour approximating the normal spillway elevation or normal pool elevation, except where Palustrine wetlands extend lakeward of that boundary. Where a river enters a lake, the extension of the Lacustrine shoreline forms the Riverine–Lacustrine boundary.

Palustrine System

Definition. The Palustrine System includes all nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses or lichens, and all such wetlands that occur in tidal areas where salinity due to ocean-derived salts is below 0.5%. It also includes wetlands lacking such vegetation, but with all of the following four characteristics: 1) the area is <8 ha (20 acres); 2) active wave-formed or bedrock shoreline features are lacking; 3) water depth in the deepest part of basin is <2 m at low water; and 4) salinity due to ocean-derived salts is <0.5%.

Limits. The Palustrine System is bounded by upland or by any of the other four Systems.

Description. The Palustrine System was developed to group the vegetated wetlands traditionally called by such names as marsh, swamp, bog, fen, and prairie pothole, which are found throughout the United States. It also includes small, shallow, permanent, or intermittent water bodies often called ponds (except in New England and New York where the term pond often refers to substantial lakes). Palustrine wetlands may be situated shoreward of lakes, river channels, or estuaries on river floodplains, in isolated catchments, or on slopes. They may also occur as islands in lakes or rivers. The erosive forces of wind and water are of minor importance except during severe floods.

Classes and Subclasses

The class is the highest taxonomic unit below the Subsystem level. It describes the general appearance of the habitat in terms of either the dominant life form of the vegetation or the physiography and composition of the substrate—features that can be recognized without the aid of detailed environmental measurements. Vegetation is used at two different levels in the classification. Five life-forms—trees, shrubs, emergents, emergent mosses, and lichens—are used to define classes because they are relatively easy to distinguish, do not change distribution rapidly, and have traditionally been used as criteria for classification of wetlands. Other forms of vegetation, such as submersed or floating-leaved rooted vascular plants, free-floating vascular plants, submergent mosses, and algae, though frequently more difficult to detect, are used to define the class Aquatic Bed. Pioneer species that briefly invade wetlands when conditions are favorable are treated at the subclass level because they are transient and often are not true wetland species (Cowardin et al., 1979).

Using life-forms at the class level has two major advantages: 1) extensive biological knowledge is not required to distinguish between various life-forms and 2) various life-forms are easily recognizable on a great variety of remote sensing products (Anderson et al., 1976) If vegetation (except pioneer species) covers ≥30% of the substrate, classes are distinguished on the basis of the life form of the plants that constitute the uppermost layer of vegetation and that occupy an areal coverage ≥50% of vegetative cover. Finer differences in life-forms are recognized at the subclass level. For example, in the C-CAP system Estuarine Woody Wetland is divided into the subclasses Scrub-Shrub and Forest categories, each of which may be further characterized as Deciduous, Evergreen, and Mixed on the basis of the predominant life-form. This differs somewhat from the Cowardin et al. system which distinguishes trees from shrubs at the class level.

If vegetation covers <30% of the substrate, the physiography and composition of the substrate are the principal characteristics used to distinguish classes. The nature of the substrate reflects regional and local variations in geology and the influence of wind, waves, and currents on erosion and deposition of substrate materials. The classes Bottoms, Shores, and Streambeds are separated on the basis of duration of inundation. In the Riverine, Lacustrine, and Palustrine Systems, Bottoms are submerged all or most of the time, whereas Streambeds and Shores are exposed all or most of the time. In the Marine and Estuarine Systems, Bottoms are Subtidal, whereas Streambeds and Shores are Intertidal. Bottoms, Shores, and Streambeds are further divided at the class level on the basis of the important characteristic of rock versus unconsolidated substrate. Subclasses are based on finer distinctions in substrate material unless, as with Streambeds and Shores, the substrate is covered by, or shaded by, an areal coverage of pioneering vascular plants (often nonhydrophytes) ≥30%. The subclass is then simply "vegetated." Further detail as to the type of vegetation must be obtained at the level of dominance type. Reefs are a unique class in which the substrate itself is composed primarily of living and dead animals. Subclasses of Reefs are designated on the basis of the type of organism that formed the reef.

As shown in Appendix Table 2, the classes defined in Cowardin et al. (1979) include

Rock Bottom (not used in the C-CAP system)
Unconsolidated Bottom (not used in the C-CAP system)
Aquatic Bed
Reef
Streambed (not used in the C-CAP system)
Rocky Shore
Unconsolidated Shore
Emergent Wetland
Scrub-Shrub Wetland
Forested Wetland

Aquatic Bed

Definition. The Aquatic Bed class includes wetlands and deepwater habitats dominated by plants that grow principally on or below the surface of the water for most of the growing season in most years. Water regimes include subtidal, irregularly exposed, regularly flooded, permanently flooded, intermittently exposed, semi-permanently flooded, and seasonally flooded.

Description. Aquatic beds represent a diverse group of plant communities that require surface water for optimum growth and reproduction. They are best developed in relatively permanent water or under conditions of repeated flooding. The plants are either attached to the substrate or float freely in the water above the bottom or on the surface. The subclasses are Algal, Aquatic Moss (not used by C-CAP and not defined here), and Rooted Vascular.

Algal—Algal beds are widespread and diverse in the Marine and Estuarine Systems, where they occupy substrates characterized by a wide range of sediment depths and textures. They occur in both the Subtidal and Intertidal subsystems and may grow to depths of 30 m (98 ft). Coastal algal beds are most luxuriant along the rocky shores of the Northeast and West. Kelp (*Macrocystis*) beds are especially well developed on the rocky substrates of the Pacific coast. Dominance types such as the rockweeds *Fucus* and *Ascophyllum* and the kelp *Laminaria* are common along both coasts. In tropical regions, green algae, including forms containing calcareous particles, are more characteristic; *Halimeda* and *Penicllus* are common examples. The red alga *Laurencia* and the green algae *Caulerpa*, *Enteromorpha*, and *Ulva* are also common Estuarine and Marine dominance types; *Enteromorpha* and *Ulva* are tolerant of fresh water and flourish near the upper end of some estuaries. The stonewort *Chara* is also found in estuaries.

Inland, the stoneworts *Chara*, *Nitella*, and *Tolypella* are examples of algae that look much like vascular plants and may grow in similar situations. However, meadows of *Chara* may be found in Lacustrine water as deep as 40 m (131 ft) where hydrostatic pressure limits the survival of vascular submergents (phanaerogams). Other algae bearing less resemblance to vascular plants are also common. Mats of filamentous algae may cover the bottom in dense blankets, may rise to the surface under certain conditions, or may become stranded on unconsolidated or rocky shores.

Rooted Vascular—Rooted Vascular beds include a large array of vascular species in the Marine and Estuarine Systems. They have been referred to as temperate grass flats (Phillips, 1974), tropical marine meadows, as well as eelgrass beds, turtlegrass beds, and seagrass beds. The greatest number of species occur in shallow, clear tropical, or subtropical waters of moderate current strength in the Caribbean and along the Florida and Gulf Coasts. Principal dominance types in these areas include turtle grass, *Thalassia testudinum*, shoalgrass, *Halodule wrightii*, manatee grass, *Cymodocea filiformis*, widgeon grass, *Ruppia maritima*, sea grasses, *Halophila* spp., and wild celery, *Vallisneria americana*.

Reef

Definition. The Reef class includes ridgelike or moundlike structures formed by the colonization and growth of sedentary invertebrates. Water regimes are restricted to subtidal, irregularly exposed, regularly flooded, and irregularly flooded.

Description. Reefs are characterized by being elevated above the surrounding substrate and interfering with normal wave flow; they are primarily subtidal, but parts of some reefs may be intertidal as well. Although corals, oysters, and tube worms are the most visible organisms and are mainly responsible for reef formation, other mollusks, foraminifera, coralline algae, and other forms of life also contribute substantially to reef growth. Frequently, reefs contain far more dead skeletal material and shell fragments than living matter. The subclasses are Coral, Mollusk, and Worm. Only the first subclass is emphasized by C-CAP; the other two definitions are omitted.

Coral—Coral reefs are widely distributed in shallow waters of warm seas, in Hawaii, Puerto Rico, the Virgin Islands, and southern Florida. Odum (1971) characterized them as stable, well-adapted, highly diverse, and highly productive ecosystems with a great degree of internal symbiosis. Coral reefs lie almost entirely within the Subtidal subsystem of the Marine System, although the upper part of certain Reefs may be exposed. Examples of dominance types are the corals *Porites*, *Acropora*, and *Montipora*. The distribution of these types reflects primarily elevation, wave exposure, and reef age.

Rocky Shore

Definition. The Rocky Shore class includes wetland environments characterized by bedrock, stones, or boulders which singly or in combination have an areal cover ≥75% and an areal coverage by vegetation of <30%. Water regimes are restricted to irregularly exposed, regularly flooded, irregularly flooded, seasonally flooded, temporarily flooded, and intermittently flooded.

Description. In Marine and Estuarine Systems, Rocky Shores are generally high-energy habitats that lie exposed as a result of continuous erosion by wind-driven waves or strong currents. The substrate is stable enough to permit the attachment and growth of sessile or sedentary invertebrates as well as attached algae or lichens. Rocky shores usually display a vertical zonation that is a function of tidal range, wave action, and degree of exposure to the sun. In the Lacustrine and Riverine Systems, Rocky shores support sparse plant and animal communities. The subclasses are Bedrock and Rubble. More detailed definitions are provided in Cowardin et al. (1979).

Unconsolidated Shore (Tidal Flats)

Definition. The Unconsolidated Shore class includes all wetland habitats having three characteristics: 1) unconsolidated substrates with < 75% areal cover of stones, boulders, or bedrock; 2) <30% areal cover of vegetation other than pioneering plants; and 3) any of the following water regimes: irregularly exposed, regularly flooded, irregularly flooded, seasonally flooded, temporarily flooded, intermittently flooded, saturated, or artificially flooded. Intermittent or intertidal channels of the Riverine System and intertidal channels of the Estuarine System are classified as Streambed.

Description. Unconsolidated Shores are characterized by substrates lacking vegetation except for pioneering plants that become established during brief periods when growing conditions are favorable. Erosion and deposition by waves and currents produce a number of landforms such as beaches, bars, and flats, all of which are included in this class. Unconsolidated Shores may be found adjacent to Unconsolidated Bottoms in all systems. As in the class Unconsolidated Bottoms, the particle size of the substrate and the water regime are the important factors determining the types of plant and animal communities present. Different substrates usually support characteristic invertebrate fauna. The subclasses are Cobble-gravel, Sand, and Mud. More detailed definitions are provided in Cowardin et al. (1979).

Emergent Wetland

Definition. The Emergent Wetland class is characterized by erect, rooted, herbaceous hydrophytes (excluding mosses and lichens) which are present for most of the growing season in most years. These wetlands are usually dominated by perennial plants. All water regimes are included except subtidal and irregularly exposed.

Description. In areas with relatively stable climatic conditions, emergent wetlands maintain the same appearance year after year. In other areas, such as the prairies of the central United States, violent climatic fluctuations cause them to revert to open water in some years. Emergent wetlands are found throughout the United States and occur in all systems except Marine. Emergent wetlands are known by many names, including marsh, meadow, fen, prairie pothole, and slough. Areas dominated by pioneer plants that become established during periods of low water are not emergent wetlands and should be classified as Vegetated Unconsolidated Shores or Vegetated Streambeds. The subclasses in the Cowardin et al. system are Persistent and Nonpersistent.

Woody Wetland

The Woody Wetland class includes any species with an aerial stem that persists for more than one season. The Woody Wetland class is divided into three subclasses: Deciduous, Evergreen, and Mixed.

Deciduous—The Deciduous Woody Wetland subclass includes all wetland forest and shrub areas having a predominance of trees and shrubs that lose their leaves or needles at the end of the frost-free season or at the beginning of a dry season. This category contains greater than two-thirds deciduous trees and shrubs. The Deciduous Woody Wetland category can be divided into three categories: Forest, Scrub-Shrub, and Dead.

Forest—Definition. Forested wetland is characterized by woody vegetation ≥6 m in height. All water regimes are included except subtidal.

Description. Forested wetlands are most common in the eastern United States and in those sections of the West where moisture is relatively abundant, particularly along rivers and in mountains. They occur only in the Palustrine and Estuarine Systems and normally contain an overstory of trees, an understory of young trees or shrubs, and a herbaceous layer. Forested wetlands in the Estuarine System, including the mangrove forests of Florida, Puerto Rico, and the Virgin Islands, are known by such names as swamps, hammocks, heads, and bottoms. These names often occur in combination with species names or plant associations, such as cedar swamp or bottom land hardwoods.

Broad-leaved Deciduous—Dominant trees typical of broad-leaved deciduous wetlands, which are represented throughout the United States, are most common in the South and East. Common dominants are species such as red maple, American elm, *Ulmus americana*, the ashes *Fraxinus pennsylvanica* and *F. nigra*, black gum, *Nyssa sylvatica*, tupelo gum, *N. aquatica*, swamp white oak, *Quercus bicolor*, overcup oak, *Q. lyrata*, and basket oak, *Q. michauxii*. These wetlands generally occur on mineral soils or highly decomposed organic soils.

Needle-leaved Deciduous—The southern representative of the Needle-leaved Deciduous Wetland subclass is bald cypress, *Taxodium distichum*, which is noted for its ability to tolerate long periods of surface inundation. Tamarack is characteristic of the boreal forest region, where it occurs as a dominant on organic soils. Relatively few other species are included in this subclass.

Scrub-Shrub—Definition. Scrub-Shrub wetland includes areas dominated by woody vegetation <6 m (20 ft) tall. The species include true shrubs, young trees, and trees or shrubs that are small or stunted because of environmental conditions. All water regimes except subtidal are included.

Description. Scrub-shrub wetlands may represent a successional stage leading to forested wetlands, or they may be relatively stable communities. They occur only in the Estuarine and Palustrine Systems but are one of the most widespread classes in the United States. Scrub-shrub wetlands are known by many names, such as shrub swamp, shrub, bog, and pocosin. The C-CAP category includes forests composed of young trees <6 m tall regardless of potential height at maturity.

Broad-leaved Deciduous—In Estuarine System wetlands the predominant deciduous and broad-leaved trees or shrubs are plants such as sea-myrtle, *Baccharis halimifolia*, and marsh elder, *Iva frutescens*. In the Palustrine System typical dominance types are alders, *Alnus* spp., willows, *Salix* spp., buttonbush, *Cephalanthus cocidentalis*, red osier dogwood, *Cornus stolonifera*, honeycup, *Zenobia pulverulenta*, spirea, *Spiraea douglasii*, bog birch, *Betula pumila*, and young trees of species such as red maple, *Acer rubrum*, or black spruce, *Picea mariana*.

Needle-leaved Deciduous—This group, consisting of wetlands where trees or shrubs are predominantly deciduous and needle-leaved, is represented by young or stunted trees such as tamarack or bald cypress, *Taxodium distichum*.

Dead—Definition. Dominated by dead deciduous woody vegetation, these wetlands are usually produced by a prolonged rise in the water table resulting from impoundment of water by landslides, human activity, or beaver activity. Such wetlands may also result from various other factors such as fire, salt spray, insect infestation, air pollution, and herbicides.

Evergreen—The Evergreen Woody Wetland subclass contains wetland forests and shrubs that do not lose their leaves or needles at the end of a frost-free season or at the beginning of a dry season. The Evergreen Woody Wetland category is subdivided into two additional categories: Forest and Scrub–Shrub.

Forest—Definition. Forested wetland is characterized by woody vegetation ≥6 m in height. All water regimes are included except subtidal.

Broad-leaved Evergreen—In the Southeast, broad-leaved evergreen wetlands reach their greatest development. Red bay, *Persea borbonia*, loblolly bay, *Gordonia lasianthus*, and sweet bay, *Magnolia virginiana*, are prevalent, especially on organic soils. This group also includes red mangrove, black mangrove, *Avicennia germinans*, and white mangrove, *Languncularia racemosa*, which are adapted to varying levels of salinity.

Needle-leaved Evergreen—Black spruce, growing on organic soils, represents a major dominant of the Needle-leaved Evergreen subclass in the north. Though black spruce is common on nutrient-poor soils, northern white cedar, *Thuja occidentalis*, dominates northern wetlands on more nutrient-rich sites. Along the Atlantic Coast, Atlantic white cedar, *Chamaecyparis thyoides*, is one of the most common dominants on organic soils. Pond pine, *Pinus serotina*, is a common needle-leaved evergreen found in the Southeast in association with dense stands of broad-leaved evergreen and deciduous shrubs.

Scrub-Shrub—Definition. Scrub-shrub wetland includes areas dominated by woody vegetation <6 m (20 ft) tall. The species include true shrubs, young trees, and trees or shrubs that are small or stunted because of environmental conditions. All water regimes except subtidal are included.

Broad-leaved Evergreen—In the Estuarine System, vast wetland areas are dominated by mangroves (*Rhizophora mangle, Languncularia racemosa, Conocarpus erectus,* and *Avicennia germinans*) that are 1 m to <6 m tall. In the Palustrine System, the broad-leaved evergreen species are typically found on organic soils. Northern representatives are labrador tea, *Ledum groenlandicum,* bog rosemary, *Andromeda glaucophylla,* bog laurel, *Kalmia polifolia,* and the semi-evergreen leatherleaf, *Chamaedaphne calyculata.* In the south, fetterbush, *Lyonia lucida,* coastal sweetbells, *Leucothoe axillaris,* inkberry, *Ilex glabra,* and the semi-evergreen black ti-ti, *Cyrilla racemiflora,* are characteristic broad-leaved evergreen species.

Needle-leaved Evergreen—The dominant species in needle-leaved evergreen wetlands are young or stunted trees such as black spruce or pond pine.

Dead—Definition. These wetland areas are dominated by dead evergreen woody vegetation. Like dead deciduous woody wetlands, they are most common in, or around the edges of, impoundments and beaver ponds. The same factors that produce dead deciduous woody wetlands produce dead evergreen woody wetlands.

Mixed—The Mixed Woody Wetland subclass includes all forest and shrub wetland areas where both evergreen and deciduous trees and shrubs grow and neither predominates. When evergreen and deciduous species each occupy ≥33% of an area, the land is classified as Mixed Woody. The Mixed Woody category is subdivided into two additional categories: Forest and Scrub/Shrub.

Forest—This category includes all forested areas where both evergreen and deciduous trees are growing and neither predominate.

Scrub/Shrub—This category includes all shrub areas where both evergreen and deciduous shrubs are growing and neither predominate.

Dead—Wetland areas dominated by dead mixed woody vegetation are, like dead deciduous woody wetlands, most common in, or around the edges of, impoundments and beaver ponds. The same factors that produce dead deciduous woody wetlands produce dead mixed woody wetlands.

Water

Cowardin et al. (1979) define deepwater habitats as permanently flooded lands lying below the deepwater boundary of wetlands. Deepwater habitats include environments where surface water is permanent and often deep, so that water, rather than air, is the principal medium within which the dominant organisms live, whether or not they are attached to the substrate. As in wetlands, the dominant plants are hydrophytes. However, the substrates are considered nonsoil because the water is too deep to support emergent vegetation. The class Water includes Marine/Estuarine, Lacustrine, Palustrine, and Riverine Deepwater subclasses as defined by Cowardin et al. (1979).

Appendix 4
C-CAP Workshops

This guidance document results from the participation of more than 200 scientists, technical specialists, managers, and regional experts in nine protocol-development workshops. Four regional workshops were held in the Northeast, Southeast, West Coast, and Great Lakes regions to address a broad range of issues including those specific to each major coastal region. Also, a major national workshop was held that focused specifically on mapping submerged aquatic vegetation. Participation was encouraged across all Federal and State agencies involved in coastal research, management, and policy and many other agencies concerned with remote sensing and land-cover analysis. The seagrass workshop followed the same format, focusing specifically on submersed habitats. Each workshop was presented with a draft C-CAP protocol, based initially on the Chesapeake Bay prototype, and participants were encouraged to refine the draft and resolve remaining issues. Issues not resolved in the five major workshops were addressed through dedicated topical workshops. Finally, the issues that could not be resolved through workshops were explored through research funding proposals.

Two accuracy assessment workshops involved leading specialists in spatial error estimation who were asked to recommend protocols for accuracy assessment of C-CAP TM data. The accuracy assessment procedures outlined in this report are a direct result of those workshops. The classification workshop was a multi-agency group organized to develop a classification system that would suit C-CAP needs. Through the workshop and a long iterative process thereafter, the classification presented in this report was developed. The Maryland Field Reconnaissance workshop was unique in that the organizers were not from C-CAP but from the Maryland Department of Natural Resources and Salisbury State University. The principal objective of the workshop was to provide recommendations concerning C-CAP products. The reconnaissance consisted of field visits to sites in the vicinity of Salisbury, Maryland, identified in a preliminary version of the C-CAP Chesapeake Bay Land-Cover Change Database. In addition, the preliminary C-CAP data were compared with other types of ancillary data supplied by workshop participants.

Findings and recommendations from these workshops and from other meetings of specialists (not listed here) were crucial in the development of this document.

Southeast Regional Workshop
Location: University of South Carolina
Columbia, SC
Dates: 29–31 May 1990
Host: University of South Carolina
Co-Chairs: Jerome Dobson
Kenneth Haddad

Seagrass Mapping Workshop
Location: Embassy Suites, Tampa Airport Hotel
Tampa, FL
Dates: 23–25 July 1990
Co-Chairs: Randolph Ferguson
Robert Orth

Accuracy Assessment Workshop
Location: National Marine Fisheries Service
Beaufort Laboratory
Beaufort, NC
Date: 25 September 1990
Host: Beaufort Laboratory
Chair: Jerome Dobson

Northeast Regional Workshop
Location: Whispering Pines Conference Center
W. Alton Jones Campus
University of Rhode Island
Kingston, RI
Dates: 8–10 January 1991
Host: University of Rhode Island
Co-Chairs: Jerome Dobson
Kenneth Haddad

Classification Scheme Workshop
Location: Silver Spring, MD
Date: 12 February 1991
Co-Chairs: James Johnston
Vic Klemas

West Coast Regional Workshop
Location: Embassy Suites Hotel
Seattle, WA
Dates: 29 April–1 May 1991
Co-Chairs: Jerome Dobson
Kenneth Haddad

Maryland Field Reconnaissance Workshop
Location: Salisbury State University
Salisbury, MD
Dates: 16–18 July 1991
Host: Salisbury State University
Workshop Design: William Burgess, Maryland Department of Natural Resources;
Edward W. Christoffers, NOAA/NMFS
Jerome Dobson, Oak Ridge National Laboratory
Randolph Ferguson, NOAA/NMFS
Adam Fisch, Virginia Council on the Environment
K. Peter Lade, Salisbury State University
James Thomas, NOAA/NMFS
Bill Wilen, USFWS, National Wetlands Inventory.
Sponsors: Salisbury State University, Maryland Department of Natural Resources, NOAA, and USFWS

Accuracy Assessment Workshop

Location: Oak Ridge National Laboratory
Oak Ridge, TN
Date: 1–2 August 1991
Host: Oak Ridge National Laboratory
Chair: Jerome Dobson

Great Lakes Regional Workshop

Location: Best Western Ann Arbor Regent
Ann Arbor, MI
Dates: 19–27 August 1991
Host: NOAA Great Lakes Environmental Research Lab
Co-Chairs: Jerome Dobson
Kenneth Haddad

Appendix 5
C-CAP Protocol Development Research

C-CAP funded research to refine various aspects of the protocol based on workshop recommendations and on findings from the upland and wetland prototype (Chesapeake Bay), the water and submerged land prototype (North Carolina Coast), and the Salisbury field experience. These research projects are intended to increase the geographical coverage of the C-CAP change detection database. The following is a list of the institutions that performed the research and the topics addressed in fiscal year 1991:

University of South Carolina
- Test change detection methodologies
- Identify optimum pattern recognition algorithms

North Carolina State University
- Develop a seamless database from two independently developed land-cover databases derived from TM data

Universities of Rhode Island and Connecticut
- Test change detection methodology
- Test the use of available digital wetlands data as an aid for classifying TM imagery

Beaufort, NMFS
- Develop change detection methodologies for SAV

An announcement of availability of funds for protocol development research was distributed in March 1992. The following five studies were funded:

University of South Carolina
- Determine the impact of tides on coastal change detection

North Carolina State University
- Develop methodologies for accuracy assessment for change detection databases

University of Virginia
- Examine influence of tides on TM data with the aid of digital elevation models

University of Maine
- Develop improved methodologies for detecting forested wetlands

University of New Hampshire
- Develop methodologies for accuracy assessment of change detection databases

Two other studies were also funded by C-CAP in fiscal year 1992:

Universities of Rhode Island and Connecticut
- Funded for six months to finish work started in 1991

Beaufort, NMFS
- Develop change detection methodologies for SAV using GPS technology.

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