REMOTE SENSING OF TIDAL WETLANDS:

MAPPING AND BEYOND

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Abstract

Remote sensing, primarily using aerial photographs, is a widely established and accepted method in mapping and inventory of tidal wetlands. Wetland habitats are recognized and the boundaries with non-wetlands are drawn primarily on the basis of interpreted vegetative cover as well as on identification of open water, beach, rocky shores, etc. Mapping by remote detection enjoys considerable advantages in speed, flexibility, and cost per area mapped over conventional techniques. With mapping and inventory applications well established, research is focusing more and more on effective sensing of functional processes within the wetlands environment. The accurate measurement of radiometric characteristics made possible by hand-held field radiometers and by aerial and orbital multispectral scanners has produced increased efforts in quantitatively relating remote measurements to environmental parameters. Because of the expense of field measurement of functional variables, use of remote sensing technology, particularly orbital sensors, would be extremely cost-effective relative to conventional methods in these applications.

1. Introduction

The history of remote sensing of tidal wetlands has corresponded closely with twenty years of growing concern for and efforts in management of this vulnerable habitat. It had long been recognized that, for those plants and animals adapted to intermittent inundation by saline waters, tidal wetlands constituted an extremely favorable environment, supporting enormous biological activity and production (Odum, 1959). In the early 1960's ecological research began to suggest that tidal wetlands played a valuable role in supporting the high biological productivity of the adjacent estuaries (for example - Odum, 1961; Teal, 1962). It also became clear that, owing to their occupation of prime coastal dumping and building sites, natural wetlands were being lost at an alarming rate. In 1963, Massachusetts began regulating the use of wetlands through legislation which established conditions for alteration of natural coastal habitat. There followed a burgeoning of state regulatory efforts including further legislation in Massachusetts (1965), Rhode Island (1965), Maine (1967), New Hampshire (1967), Connecticut (1969), and New Jersey (1970) (Lagna, 1975). Beginning with Connecticut's in 1969,

wetlands legislation generally mandated statewide inventories so that the boundaries of the regulated resource could be more clearly defined. The Federal "Coastal Zone Management Act" of 1972 gave further impetus to state management and inventory efforts and, by 1976, every state having ocean or estuarine coastline had initiated some form of wetland inventory (U.S. Fish and Wildlife Service, 1976).

While the intent of all of these efforts was substantially clear, implementation proved to be problematical. Definitions of "wetlands" varied considerably from state to state. Many were originally defined by their relationship to mean high water (MHW) because of the historic importance attached to this datum in determinations of public versus private ownership. It was soon apparent, however, that this legal boundary often bore little relationship to the functional boundaries of the ecosystem which the statutes were intended to protect (Lagna, 1975). Further, the MHW datum, or any other line of constant elevation relative to sea-level, is enormously difficult to identify, map and update on the flat, soft, vegetated surface of the tidal marsh (Hawkes, 1966; Fornes and Reimold, 1973). Even small errors in vertical positioning can cause changes in the designation of very large areas on the gently sloping marsh surface (Garretson, 1968). The result is that, when applied over large areas, conventional ground surveys of wetland boundaries are time-consuming and expensive to conduct, especially as any inventory requires frequent repetition (every five to ten years) to monitor the effects of erosion, accretion, subsidence and other dynamics of wetland physiography. What was needed was a fast, economical and accurate technique for mapping and inventorying large expanses of wetland.

The obvious alternative to ground surveys was use of remote sensing technology. Problems of difficult access in wetlands were overcome and inventories could be conducted quickly and for a fraction of the cost of conventional surveys. Most state and federal inventories utilize some form of remote sensor data, usually aerial photographs, and the majority rely on remote sensing as the primary information source (Carter, 1978).

Having reached an operational phase for mapping and inventory, development of new remote sensing applications in tidal wetlands continues to parallel developments in management priorities and in ecological research. Pressure for development

requires managers to make judgements of relative value in different wetland areas. At the same time, earlier assumptions concerning ecological values of wetlands are being subjected to increasingly critical examination by the scientific community. The hypothesized subsidy of estuarine production by "outwelling" of wetland detritus, for example, is the subject of some controversy and, at the least, appears to be highly variable from site to site (e.g. Haines, 1977; Nixon, 1980). Information on functional wetland processes is thus required in addition to the data provided by boundary mapping programs. In this area, too, remote sensing has major contributions to make although the sensing and interpretation techniques used will be substantially different from mapping methods and will require further development.

2. Remote Sensing for Wetland Mapping and Inventory

Operational inventories of wetland boundaries rely primarily on identification of plant species or associations. It is usually assumed that designated "wetland" vegetation will not be found to any significant degree outside of the saline or brackish zone and therefore that their presence is indicative of an intertidal wetland and the contiguous saline or brackish areas. In some states the transition from one species or growth form to another is identified with a particular tidal datum - MHW for instance. However, although tidal inundation certainly is a controlling factor in marsh plant zonation, attempts to correlate particular species unambiguously with a specific tidal plane have generally been unsuccessful. Species and associations of plants retain their relative vertical relationships from place to place, but their exact position with regard to a tidal datum is highly site specific (Fornes and Reimold, 1973; Lagna, 1975). Nevertheless, in practice, it is vegetation which is usually used to delineate wetlands because of the difficulties inherent in applying elevation criteria. Some discrepancies with legal definitions of public vs. private jurisdiction may have to be resolved with on-site investigations but, as it is the wetland ecosystem which is being managed, biological criteria ultimately seem less arbitrary than those based solely on elevation.

Most wetland inventories in the United States are based on aerial photography supplemented by field work and other data sources (Carter, 1978). The identification and mapping of vegetation have been among the most persistent and well-developed applications of remote sensing for many years. For the most part, vegetation is easily distinguished from other types of cover on the basis of its unique spectral reflectance characteristics. The importance of pigments in photosynthetic function results in visible color being a useful diagnostic characteristic of the condition of vegetation as well as discriminating it from non-vegetated surfaces. In addition, reflectance in the near infrared portion of the spectrum can be related to indicators of the physiological status of vegetation as well as aiding in discrimination of plant species and associations.

It appears that most common film and filter combinations, including panchromatic, can be used to delineate wetlands from uplands as the distinction is often based on obvious textural and topographic differences between wetland plants and upland trees, shrubs, crops or fill. Stereoscopic viewing is frequently used to discriminate breaks in slope and sharp changes in elevation or canopy height occurring at wetland boundaries (Garvin and Wheeler, 1973). The presence of more subtle boundaries and the desire to differentiate species associations within the wetlands have led to a general preference for the high spectral information content of color-infrared photography (Carter, 1978; Brown, 1978; McEwen et al., 1975). Sensing in the infrared regions of the spectrum also aids in the delineation of the wetland/water boundary due to high contrast between vegetation and highly absorptive water. Atmospheric haze effects encountered at shorter visible wavelengths are also reduced. As with any other remote sensing application, no realistic inventory can be performed without field work for establishing interpretation criteria and validating final results. Direct identification of plant species is, of course, possible only in situ - interpretation of photographs can only extrapolate the investigator's personal knowledge of the species present and their patterns of occurrence.

An extensive commercial capability for aerial mapping is present in the U.S. and many other parts of the world. The scale of photography is easily adjusted to the scale, format, cost and accuracy requirements of particular mapping tasks. When wetland boundaries must be related to holdings of individual property owners, a large mapping scale of 1:2400 has been used (Anderson and Wobber, 1973; Bartlett et al., 1976). Smaller scales ranging from 1:20,000 to 1:500,000 have also been employed in state inventories (Carter, 1978). Planimetric precision of the final product can be selected based on inventory requirements. Boundaries can be interpreted and displayed on the original aerial photography - an efficient method when map accuracy is not necessary (Bartlett et al., 1976). When conformance with National Map Accuracy Standards is required, photo-interpreted boundaries can be plotted on a standard cartographic base, or photogrammetric techniques can be used to correct for photographic distortions and the boundaries are drawn on the photos themselves (Anderson and Wobber, 1973). Use of the photographs as a representational base has several advantages whether or not map accuracy is desired. The photos often show relationships of buildings, vegetation and other landmarks which may not be present on standard maps. In many cases, the interpretive criteria applied for positioning a particular boundary are obvious from the photograph, simplifying resolution of disputed designations. The positions of changing shorelines are usually more up-to-date on recent photography than on available maps. Perhaps most important, a photograph has a compelling and easily grasped impact as evidence, particularly for the layman, even when a map might depict the same relationships. As a result, several inventory programs have used a photo-based final product

(Brown, 1978 ; Garvin and Wheeler, 1973; Bartlett et al., 1976).

Inventories of tidal wetlands are often of interest for reasons other than statutory boundary delineation. The magnitudes of many important wetland functions are directly related to the local extent of the tide marsh ecosystem. As a result, many inventories of wetlands have been performed as a guide to the extent and character of the resource and its impact on adjacent estuarine waters. In most cases, requirements for planimetric accuracy are not as stringent as when statutory boundaries are desired. The result is that the investigator has greater freedom in choosing the scale of the final product and thus may utilize imaging systems at higher altitudes or with less spatial resolution, with accompanying reductions in cost. The "National Wetlands Inventory" is being conducted by the U.S. Fish and Wildlife Service based on aerial photography, producing both a digital data base and maps at 1:100,000 (Montanari and Townsend, 1977). This inventory also identifies shallow open water habitats by bottom type and geomorphic setting (e.g., estuarine, riverine, lacustrine, etc.).

Data from the Landsat satellite multispectral scanner (MSS) have been used for inventorying wetlands at a variety of scales (Anderson et al., 1974; Carter and Schubert, 1974; Klemas et al., 1975; Butera, 1979). Landsat inventories have generally been experimental in nature and, while large wetland areas have been successfully identified and classified into dominant vegetation categories, the spatial resolution of the scanner data has restricted its application for operational inventories (Carter, 1978). Nominal ground pixel size for the current Landsat-MSS is 0.45 ha making boundary location difficult, particularly for small or narrow marshes. Carter (1978) suggests that a pixel size less than approximately 0.25 ha is required for effective interface of orbital data with operational inventories. The next generation of Landsat Earth resources scanner (the Thematic Mapper - launched in July, 1982) achieves a nominal pixel size of approximately 0.1 ha, enhancing the potential utility of orbital data.

Orbital scanner data suffer from a further disadvantage relative to aerial photography in that no textural information is available to aid in interpretation of cover types. Interpretation relies primarily on spectral criteria because the resolution of the scanner data does not depict the fine differences in texture produced by different canopy structures. Accuracy of classification of MSS data into wetland vegetation units has been reported to range from 75% to 95% (Butera, 1979; Klemas et al., 1975). Reliance on spectral interpretation criteria does have advantages - primarily in that semi-automated digital interpretation can be employed. For inventories of large areas this can produce very large reductions in cost.

Cost is normally the overriding consideration in choosing an inventory methodology once minimum standards of scale and accuracy have been

established. In fact, inventory standards are rarely determined a priori, but are "traded-off" with cost considerations in planning the inventory process. In many states, for example, the MHW line or some datum referenced to MHW would be the preferred boundary for wetland mapping. The expense associated with mapping this datum, however, has led to alternative definitions based on vegetation - definitions compatible with less costly remote sensing methods.

Comparative costs for inventory techniques are difficult to obtain for a general case. A general idea of relative costs can be gained from figures cited in the literature [Note: All dollar figures are discounted to 1982 dollars assuming an annual inflation rate of 10% from the date of the referenced study]. The EPA has estimated its costs for an in-the-field inventory of a cordgrass marsh at \$22.00/ha (Butera, 1979). A large scale (1:2400) wetland inventory based on 1:12,000 color and color-infrared photography was conducted in Delaware for \$4.40/ha (Bartlett et al., 1976). Smaller scale vegetation inventories (not wetlands) in the Midwest used high altitude aerial photography to produce 1:24,000 and 1:250,000 scale maps for \$0.48/ha and \$0.05/ha, respectively (Eastwood et al., 1977). Butera (1979) computed costs of \$0.04/ha for a Landsat-MSS inventory of 3900 km² of wetlands in Florida. Imagery was interpreted through digital processing of the MSS data. The efficiency of semi-automated interpretation is such that as larger areas are inventoried, incremental Landsat-MSS costs fall to \$0.01/ha or less (Eastwood et al., 1977; Gaydos, 1978). Figures for specific projects will, of course, vary about those cited and these figures should be used for comparative purposes only.

The most precipitous drop in unit cost occurs in the transition from conventional surveys to large scale (i.e., low altitude) remote mapping. There are also large reductions in cost related to decreasing the scale of a remote sensing inventory. Use of Landsat-MSS data becomes cost-advantageous for inventories of large areas ($\geq 10,000$ km²) if the loss of spatial resolution and classification accuracy can be tolerated. Costs for use of Landsat-Thematic Mapper data will most likely be comparable to MSS costs - but with an approximate factor of four improvement in spatial resolution. There should also be significant improvements in classification accuracy using Thematic Mapper data because of improved spectral resolution and radiometric sensitivity.

There can be little doubt about the reliability and cost-effectiveness of aerial photographic wetland inventories. Savings of an order of magnitude or more in time and expense over conventional surveys can be achieved without significant loss of accuracy. The utility of orbital sensors is restricted, primarily by spatial resolution, to inventories of large areas at small scales or, perhaps, to rapid updating of existing maps. As we shall see, however, orbital data have advantages which make it well-suited to other data-gathering applications in wetlands.

3. Remote Sensing of Functional Variables in Tidal Wetlands

Information other than the location of boundaries and distribution of wetlands is required for effective management. This has become especially clear as early models of wetland functions and values are replaced by more complex ones in which important processes are recognized as extremely variable in time and space (see, for example, Nixon, 1980). The mere presence of a wetland no longer suffices as testament to a habitat having high ecological value (although this may be sufficient for other types of value). Criteria for judgement of relative value are available based on local variation in factors such as hydrography and primary production (Silberhorn et al., 1974). We might call such variables "functional" as they relate to the functions of the ecosystem. Generalized assumptions concerning these factors can sometimes be based on knowledge of species distributions and extent (Ibid.) but significant intraspecific variation is common. Further, there are large variations from place to place and seasonally in the characteristics of a particular species. Collection of functional data is sometimes carried out in the field but such studies can be even more time-consuming and expensive than a field inventory. Thus, if remote sensing can be applied to such measurements, large benefits could be obtained.

Recent developments in ecology have provided further motivation for applying remote sensing to assessment of wetland processes. Growing interest in global biogeochemical cycles, particularly that of carbon, has led to recognition of the Earth's vegetation as a major source/sink/transport term in material budgets (Bolin et al., 1979). Wetlands constitute a potentially important, but largely unevaluated, sink for atmospheric carbon because of their high primary productivity (Ibid.). They are also large potential sources of biogenic gases such as methane and hydrogen sulfide (Ibid.). Remote sensing offers the only effective means of assessing wetland processes on the scale required for research on global biogeochemical cycles.

An example of an important wetland process for both management and research interests is primary production. Primary production in tidal wetlands is commonly assessed through periodic measurement of biomass, usually by harvesting of measured quadrats of vegetation (e.g. Smalley, 1959). Typically, vegetation within a 0.25 to 1.0 m² quadrat is harvested and returned to the laboratory for sorting into live and dead fractions, drying and weighing. The process requires significant manpower in the field and lab. Hardisky et al. (unpublished manuscript) estimate 0.33 mandays per sample was required for travel, sampling and lab work during an assessment in Delaware marshes. As a result, productivity measurements tend to be available only intermittently for local management purposes and not at all for regional and global scale assessment.

Several studies have indicated that biomass information can be acquired through remote sensor

measurements. The most promising technique uses a difference or ratio of upwelled radiance measurements in two spectral bands (one infrared, the other in the "red" wavelength region) as an indicator of the amount of live vegetation present in the canopy (Tucker, 1979). The method is based on the high contrast in reflectance between vegetation and soil in the infrared and between live (i.e. green) and dead vegetation in the "red". Bartlett and Klemas (1980, 1981) found high correlation ($r = 0.90$) between the Landsat-MSS Band 7/Band 5 reflectance ratio and green biomass for the common wetland cordgrass: *Spartina alterniflora*. Hardisky et al. (in press) obtained similar results using spectral wavebands identical to those which will be available from the Thematic Mapper instrument. Both studies were conducted in the field using hand-held radiometers.

The requirement of this technique for accurate measurement of spectral radiance effectively excludes aerial photography as a quantitative tool but is well-suited to existing multispectral scanners. The processing steps for digital analysis of multispectral scanner data are essentially the same whether it is an inventory of cover types or a spectro-radiometric estimate of biomass which is desired. Thus, costs for biomass assessment would add only a small amount to resources required for wetland inventories using scanner data. Field or photographic boundary inventories combined with field measurements of biomass, on the other hand, require two separate methodologies adding greatly to the time and resources required. Remote assessment of biomass would therefore be extremely cost-effective relative to alternatives. Aerial scanners could be applied, as could field radiometers, for assessment of relatively small areas with significant savings in the manpower required. However, I believe that it is with orbital sensors that the future of remote biomass detection lies. Fine spatial resolution is not as important for biomass estimates since it is the magnitude and extent of biomass units and not their precise boundaries which is of greatest concern. For research in global wetland biomass and production, of course, the coverage characteristics of orbital sensors are a virtual requirement. Further, as periodic measurements during the growing season are required for production calculations, orbital sensors have a large advantage in efficiency over aerial or field missions which incur significant start-up costs for each repetition of the data collection process.

Research and development in the use of remote sensors for process-oriented measurements, including that of biomass, must continue before widespread acceptance is achieved. The effects of different plant species, climatic and tidal conditions, and atmospheric perturbations on the interpretation algorithms already developed need to be assessed. Biomass estimates might be used for purposes other than calculation of primary production. For example, biomass of *S. alterniflora* is influenced by anaerobic conditions in the marsh soil (Howes et al., 1981). Measurements of relative biomass of this species may, therefore, be related to potential for production of biogenic

gases by obligate anaerobes requiring highly reduced soils. Potential for incorporation of other important variables such as composition of intertidal waters has yet to be explored. There can be no doubt, however, that as requirements for more ecological data over larger and larger areas of the Earth grow, so too will the application of orbital remote sensing technology to measurements of functional variables.

4. Conclusions

Approximately fifteen years of operational experience has resulted in routine reliance on aerial photographic remote sensing for inventory and mapping of tidal wetlands. Current requirements for functional wetlands data such as plant biomass and productivity by both management and research interests have produced recent developments in remote sensing measurement technology. Advantages in radiometric accuracy, speed, efficiency for large areas and for frequent repetitive measurements argue strongly for use of orbital multispectral scanners in applications of this kind.

5. References

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