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Remotely Sensed Data for Ecosystem Analyses: Combining Hierarchy Theory and Scene Models

STUART R. PHINN*
DOUGLAS A. STOW
JANET FRANKLIN
Department of Geography
San Diego State University
San Diego, California 92182-2493, USA

LEAL A. K. MERTES
JOEL MICHAELSEN
Department of Geography
University of California at Santa Barbara
Santa Barbara, California 93106, USA

ABSTRACT / Remotely sensed data have been used extensively for environmental monitoring and modeling at a number of spatial scales; however, a limited range of satellite imaging systems often constrained the scales of these analyses. A wider variety of data sets is now available, allowing image data to be selected to match the scale of environmental structure(s) or process(es) being examined. A framework is presented for use by environmental scientists and managers, enabling their spatial data collection needs to be linked to a suitable form of remotely sensed data. A six-step approach is used, combining image spatial analysis and scaling tools, within the context of hierarchy theory. The main steps involved are: (1) identification of information requirements for the monitoring or management problem; (2) development of ideal image dimensions (scene model), (3) exploratory analysis of existing remotely sensed data using scaling techniques, (4) selection and evaluation of suitable remotely sensed data based on the scene model, (5) selection of suitable spatial analytic techniques to meet information requirements, and (6) cost–benefit analysis. Results from a case study show that the framework provided an objective mechanism to identify relevant aspects of the monitoring problem and environmental characteristics for selecting remotely sensed data and analysis techniques.

Environmental monitoring and modeling applications from local to global scales commonly use remotely sensed data; however, the limited variety of imaging systems often constrained the scales of these analyses. Successful launches of commercial and government satellites over the past and next five years will result in a significant increase in the number of available satellite based imaging sensors. By the year 2005 there are expected to be up to 30 satellites with spatial resolutions ranging from 0.3 m to 2.5 km and multispectral to hyperspectral wavebands (ASPRS 1996, Aplin and others 1997, Stoney 1997). An increased variety of image data sets and image-based map products will be available for use, allowing the scale of environmental structure or processes being examined to determine the most suitable image data. In the past, use of remote sensing to address problems in terrestrial ecology was constrained to a limited number of data sets. A few explicit approaches were provided to determine appropriate scale at which to acquire and process image data (Roughgarden and others 1991, Marceau and others 1994; Atkinson 1997, Barnsley and others 1997, Stein and others 1998, Green and others 2001, Franklin 2001). Given the expected increase in the variety of image data sets becoming available and the recognition of explicit natural scales of ecological structures and processes, it is paramount to develop a framework or science of scale that explicitly links: (1) the scale(s) at which information on environmental structures or processes is required; and (2) suitable image data sets (Marceau 1999, Marceau and Hay 1999). This will be achieved by integrating techniques and elements of theory for selecting appropriately scaled remotely sensed data and analysis techniques.

A framework has been developed by combining concepts from remote sensing, spatial analysis, and landscape ecology to provide environmental scientists and managers with an objective basis for selecting "optimal" data sets and analysis methods. The framework was initially developed for coastal environments due to the urgent need for effective monitoring programs in these regions in response to their high population levels, resource utilization, and disturbance levels. This paper outlines a modified version of the framework developed by Phinn and Stow (1996), Phinn (1997, 1998)

KEY WORDS: Scene model; Hierarchy theory; Optimal scale; Landscape ecology; Remote sensing

*Author to whom correspondence should be addressed at School of Geography, Planning & Architecture, The University of Queensland, Brisbane, Queensland, Australia; *email:* s.phinn@uq.edu.au.

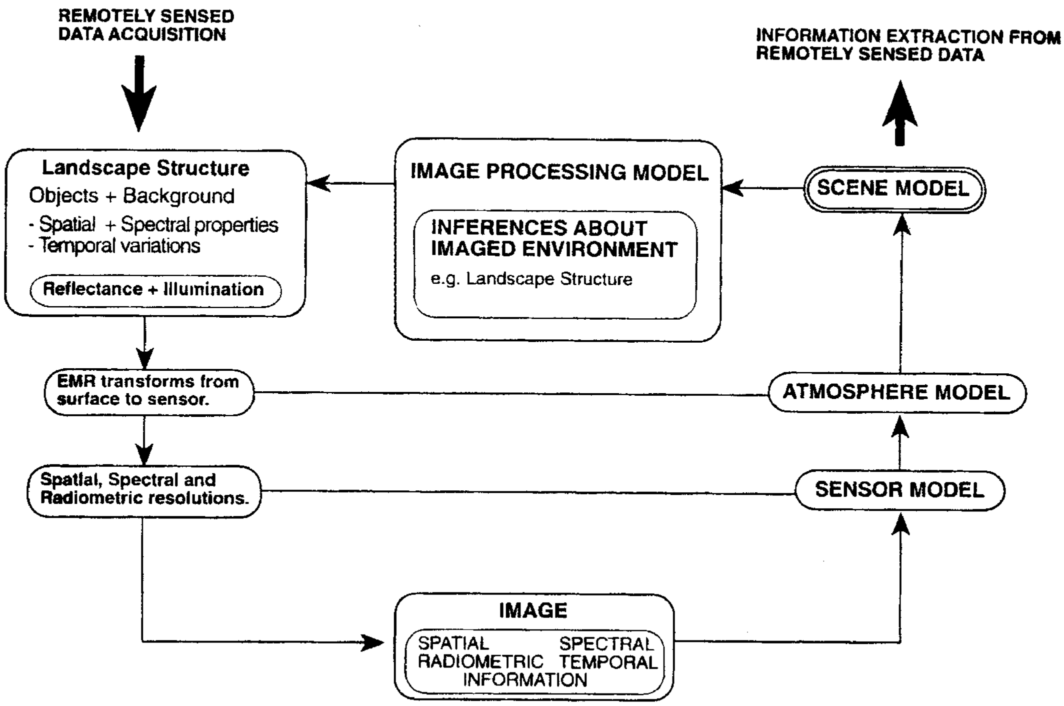

Figure 1. The data flow in remote sensing and various models used. Modified from Graetz (1990:19), Phinn (1998:3458), and Phinn and others (2000b).

and Phinn and others (2000a, b), in a format that can be used by general environmental scientists.

The framework developed by Phinn (1997, 1998) relies on the premise that the component structures and processes of an environment can be treated as a scalar hierarchy, with attributes occurring at specific spatial and temporal scales (Allen and Starr 1982, Strahler and others 1986, Hay and others 2001). In its current and future forms, remotely sensed data offer a true multiscale sampling tool and an optimal data set can be chosen by identifying the spatial scale of an environmental structure or process of interest and then selecting an image data set also collected at that scale or aggregating fine spatial resolution data (Atkinson 1997, Curran and others 1997, Cracknell 1998, Frohn 1998, Hay and others 2001). By identifying component structures and their characteristic scales in an environment using spatial statistics and constructs from hierarchy theory or a modified form of hierarchy theory, such as the hierarchical patch dynamics paradigm (Wu 1999), specific structures or processes relevant to a monitoring project can be delimited and identified as the target elements for a scene model (Strahler and others 1986). The scene model defines how an environment will appear when imaged by a remote sensing system (that has specific sampling dimensions). Working backwards from the landscape element to a scene model (Figure 1), appropriate remotely sensed data dimensions are set to enable detection and measurement of the focal scale structure or process (landscape element). Hence, the output from the framework is a scene model defining the dimensions of an ideal image data set required to collect information on a landscape structure or process of interest.

Although the necessary techniques and elements of theory exist for selecting appropriately scaled or aggregated remotely sensed data and analysis techniques, they have not been integrated explicitly to meet environmental monitoring needs. Approaches for selecting the scale(s) of remotely sensed data for examining specific environmental structures or processes have focused intensively on the use of spatial statistics and have been reviewed in Woodcock and Strahler (1987), Garcia-Moliner and others (1993), Marceau and others (1994), Quattrochi and Goodchild (1997), Stein and others (1998), Wulder and Boots (1998), and Marceau and Hay (1999). Hierarchy theory has been applied extensively to examine the spatial and temporal ordering of environmental structures and processes (e.g., Meentemeyer 1989, O'Neill and others 1989, Walker and Walker 1991, DeAngelis and White 1994, Yool 1999); however, it has only been applied in a limited sense to establish the components of an environment, their characteristics scale(s), and then remotely sensed data were matched to these scales (Hay and others 1997, 2001, Phinn and others 2000a, b). The following sections present a more detailed explanation of the framework for use in environmental monitoring and management. To demonstrate the framework's applicability, results from an environmental monitoring program in wetlands of southern California that was designed with and without the framework are presented.

Methods—The Framework

The components of the framework for selecting a suitable type of remotely sensed data for a mapping or monitoring project concerned with ecological variables are listed below, and the following text provides an explanation of how to implement the framework: (1) identification of information requirements for the mapping or monitoring problem, (2) scene model specification based on information required and environment type, (3) exploratory analysis of existing remotely sensed data, (4) selection and evaluation of suitable remotely sensed data based on the scene model, (5) selection of suitable spatial analytic techniques to meet information requirements, and (6) cost–benefit analysis.

Identification of Input Information Requirements

Several basic types of information on the mapping or monitoring project should be identified first to link the data and information required on vegetation structures and their measurement or representation in remotely sensed data at specific scales. The project specifications determine the type of information required, environment type, scale(s) of required information, acceptable error levels, available time and finances, and whether a prescribed processing technique is to be used. For coastal environments, the framework references a coastal classification system developed in Phinn (1997) to define the characteristic spatial and temporal scales of structures and processes in the environment to be monitored. For other environments, relevant literature or knowledge of the area should be used to identify the key environmental structures or processes. These information requirements are summarized in tabular format and then used to identify remotely sensed data requirements.

Scene Model Specification

Information requirements associated with an environmental mapping or monitoring project should be organized using concepts from ecological hierarchy theory and image spatial analysis to specify how the target environment should appear in remotely sensed data. The scene model provides such a construct, implicitly linking hierarchy theory and remotely sensed data by specifying which environmental elements can be identified from an image with specific spatial dimensions (Hay and others 1997, 2001). For example, if average canopy diameter for extensive areas of forested landscape is required as input to a faunal habitat suitability model, a hierarchical model (Franklin and Woodcock 1997) links tree canopy parameters characterizing forest stands to forest cover types. This dictates that sensor spectral resolution should distinguish tree canopy from background, and spatial (pixel) dimensions should range between subcanopy size and not more that several times canopy size, depending on whether H- or L-resolution information extraction methods are used. The scene model provides a standardized format in which all the relevant scalable dimensions of remotely sensed data are identified for a specific application. These include the spatial, spectral, radiometric and temporal dimensions (Table 1).

Depending on the minimum scale or smallest target feature to be identified and the extent of the project area, a recommendation is made on both the dimensions of the ground-resolution-element (GRE) or pixel size and image extent, to enable the environmental structure or process of interest to be detected by the imaging system. Published research or recent field data on the reflectance or absorption characteristics of the prevalent features in the project environment are then examined to select the sensor type, spectral bands, and radiometric sensitivity most suited to discriminating scene elements or to estimating their condition. Temporal dimensions specify the optimum time and repeat frequency for collecting remotely sensed data to maximize the extraction of required information. Temporal dimensions for the scene model are identified from the project's temporal constraints, any multitemporal analysis requirements and the characteristic temporal variability of the environmental structure or process of interest. When a processing technique is prescribed with the information requirements, the scene model parameters are specified with reference to the spatial, spectral, radiometric and temporal requirements of the processing technique. Similar to the "Information Requirements" section, the scene model specifications are summarized in tabular format, e.g., for the coastal environment (Table 1).

2.3 Exploratory Analysis of Available Remotely Sensed Data

Once identified, the ideal image dimensions specified in the scene model can be tested by using them to

Table 1. Draft scene model specifications (ideal image dimensions) for a data set to estimate projective foliage cover in a restored southern California wetland

Information required	biophysical parameter (horizontally project foliage cover), % cover in each vegetation species patch
Spatial scale	grain = smallest vegetation patch, 0.5–1.0 m
	extent = wetlands complex, 5 × 2 km
Temporal scale	one image per year at time of maximum spectral separability for all vegetation cover types
Environment type	restored tidal saltmarsh
Components and hierarchy	constraint = wetland vegetation complex
	focus = vegetation species patches
	mechanism = individual plants
Spatial dimensions	H-resolution
	grain = 0.5–1.0 m
	extent = 3.14 × 1.57 km
	interannual: match pixel sizes and ensure accurate geometric registration.
Temporal dimensions	Optimal date = June or July
	Solar conditions = 0°–20° zenith angles (11:30 am − 2 hours) (12:30 pm + 2 hours)
	tidal conditions = mean low tide (at least <+1.5ft MSL)
	interannual: near anniversary dates and acquisition times
Spectral dimensions	red 600–680 nm
	NIR 750–900 nm
	interannual: match spectral band centers and widths
Radiometric dimensions	grain (quantization): 0.01 (reflectance)
	extent (dynamic range): green (0.04), red (0.07), and NIR (0.14)
	interannual: match quantitation and dynamic range
Error tolerance levels	patch boundary delineation < minimum patch size
	vegetation species' patch labeling
	regression model cover estimate error for each vegetation cover type (<±5%) and overall relationships used must have $R^2 > 0.85$

analyze extant remotely sensed data for the mapping or monitoring site. Four steps are followed in this procedure. In the first step any preprocessing steps already applied to extant remotely sensed data are identified in order to build a data lineage. The most critical parts of exploratory spatial data analytic (ESDA) approach are the techniques applied to estimate spatial dimensions of environmental structures or processes present in an image data set (Garcia-Moliner and others 1993, Marceau and others 1994, Hay and others 1997, Frohn 1998, Griffiths and Mather 2000). ESDA approaches range in complexity from visual interpretation based on scene models (Strahler and others 1986) to image classification, segmentation, and spatial structure functions to quantify the dimensions of dominant spatial features in the scene. Spatial statistical functions, such as semivariograms, and multiscale decompositional techniques, such as wavelet analyses and object specific analysis/upscaling, have been successfully applied to identify characteristic spatial scales of environmental structures and processes in images (Woodcock and others 1988, Cohen and others 1990, Phinn and Stow 1996, Curran and others 1997, Phinn and Hill 1998, Frohn 1998, Stein and others 1998, Wulder and Boots 1998, Hay and others 2001). Similarly, the specifications for spectral and radiometric dimensions are verified based on analysis of representative samples of pixel digital numbers (reflectance or radiance) for each scene element. Finally, temporal dimensions can be assessed by examining the spatial, spectral, and radiometric dimensions as described above for image data sets from multiple dates.

Specification and Evaluation of Remotely Sensed Data

Specification of suitable remotely sensed data entails examining the ideal data dimensions set out in the scene model in relation to the spatial, spectral, radiometric, and temporal dimensions of commercially available image data sets. A compliance matrix approach is applied to evaluate which remotely sensed data sets meet or can be transformed to meet the ideal spatial, spectral, radiometric, and temporal specifications. The compliance matrix is constructed with one column listing the scene model dimensions, the next column containing dimensions of the available data (e.g., Table 2). The specified scene model and available data dimensions are compared and labeled as suitable, unsuitable, or able to be transformed to match. If the transform option is specified, a data rescaling approach is pre-

Table 2. Compliance matrix for comparison of candidate image data sets to ideal data set (scene model) for Sweetwater Marsh restoration monitoring problem

Parameter	Scene model	Data, ADAR 5500 10 Jun 95, 27 Jul 96	Level of match		Transform option
Spatial					N/A
Pixel size	0.75–2.0 m	0.72 m, 0.75 m	suitable		
Scene extent	3140 × 1570 m	5000 × 2000 m	suitable		
H/L resolution	H	H	suitable		
Spectral					N/A
No. of bands	2				
Position of bands	red 600–680 nm	red 610–680 nm	suitable		
	NIR 750–900 nm	NIR 780–1000 nm	suitable		
	NDVI	NDVI	suitable		
Radiometric					N/A
Quantization levels	0.01–0.05 (R_L)	0.0003 (R_L) (Stow and others 1996)	suitable		
Dynamic range	red 0.07 (R_L)	red	unable to assess		
	NIR 0.14 (R_L)	NIR			
Temporal			June	July	N/A
Date	June or July	10 Jun 95, 28 Jul 96	yes	yes	
Solar time	0°–20° solar zenith 10–11:30 am, 12:30–2 pm	11.45am, 1.30pm, 2.30pm (DST = PST + 1hr) +1.5ft, +1.4ft	yes	yes	
Tide levels	less than +1.5ft MSL		yes	yes	
Interval between images	12 months	no 6/94 available 8/93, 8/95 available	no	yes	
Error levels			N/A		N/A
Types	patch delineation patch labeling	not processed			
Magnitude	delineation error < minimum patch size				
Level of processing	field checked image maps	not processed	N/A		N/A
Time + cost	not specified	N/A	N/A		N/A

sented to change the spatial, spectral, or radiometric dimensions to those that are required.

Selection of Spatial Analytic Technique(s) to Provide Required Information

Selecting the spatial analytic technique(s) to be applied to the remotely sensed data as specified by the scene model is a two-step process. In the first step, the type of information required is used as the basis for identifying a broad grouping of spatial analytic techniques capable of providing the information. Three broad categories of spatial analytic techniques were identified based on the similarities in the type of output information they produce, as listed below (see Phinn 1997 for full description): (1) landscape composition analyses to identify components of the landscape that have not been categorized or classified into nominal land-cover classes; (2) landscape element pattern analyses applied to image data categorized into nominal land-cover classes, and spatial structure analyses applied to continuous data, to quantify dimensions of their pattern and distribution; and (3) quantification and mapping of biophysical parameters from empirical or deterministic inversion of remotely sensed data to estimate physical dimensions and characteristics of features controlling their reflectance.

In the second step, once a broad grouping of spatial analytic techniques has been identified as matching the information requirements of the project, suitable individual analytic approaches can be selected. Selection of a suitable approach is achieved by evaluating each of the following five criteria in relation to the information from the scene model and evaluation of available remotely sensed data: (1) Remotely sensed data specifications meet the assumptions and input requirements for the selected technique. (2) The output information from application of the technique has error levels within those acceptable to the mapping or monitoring problem. (3) Output information is at the appropriate spatial and temporal scales for the scene model and the mapping or monitoring problem. (4) Output information can be obtained within temporal and financial con-

Table 3. Information requirements for the case studies

Requirements	Case study 1: southern California wetlands	
Type of information	Landscape composition	Biophysical parameters
Environment type	Restored tidal saltmarsh	Restored tidal saltmarsh
Grain and extent required	Minimum vegetation species patch size was for cordgrass patch <1.0 m Vegetation/substrate dominance and marsh cover type maps for the restored wetland area, approx. 45 acres or 5 × 2 km	Minimum vegetation species patch size was for cordgrass patch <1.0 m Vegetation cover estimate maps for the restored wetland area, approx. 45 acres or 5 × 2 km
Temporal scale	One image per year for cordgrass mapping	One image per year prior to field sampling home ranges
Error types and levels	Types: Patch boundary delineation Labeling errors for vegetation and marsh cover types Levels: Patch boundary delineation must be within minimum patch dimensions Labeling errors tolerable will depend on areal extent and importance of class	Types: Marsh cover boundary delineation Labeling errors for marsh cover types Cover estimations from model Levels: Patch boundary delineation must be within minimum patch dimensions Labeling errors tolerable will depend on areal extent and importance of class Cover estimate error for each pixel must be less than ±5%

straints. (5) Output information is in a format that can be used directly or combined with other data as required.

A technique is selected if it meets all of the criteria specified above. Techniques may be evaluated until one is found that meets the most number of criteria.

Cost–Benefit Analysis

Assessment of the criteria identified in the five subsections above should provide specifications for selecting remotely sensed data capable of addressing the initial environmental mapping and monitoring question. If there are a number of data sets that meet the desired criteria, then the most important selection criteria may be the financial and temporal resources available for the project. In these cases a cost–benefit analysis can be derived. The costing structure is derived by incorporating data purchase fees and person hours worked on the projects. A frequently used benefit measure is the overall accuracy of the output product. This approach requires trial processing for each application problem to identify data costs, image processing fees, and field assessment. Green and others (1996, 2001) developed and applied this approach to provide a quantitative comparison of airborne and satellite image data sets for mapping habitat and structural parameters in tropical coastal environments, while Phinn and others (2000b, 2001) applied a similar approach for monitoring environmental indicators in tropical forests.

Application of the Framework

To demonstrate the procedures and the benefit derived from the framework, its application in one project is presented in the following section. Other applications of the framework, with less detailed descriptions of its theoretical basis and benefits, have been presented for mapping wetland vegetation composition on a regional scale in the wet–dry tropics in northern Australia (Phinn and Hill 1998, Phinn and others 1999, 2000a), mapping urban growth in a coastal catchment (Phinn and Stanford 2001), and evaluating the feasibility of remote sensing for monitoring environmental indicators in tropical forests (Phinn and others 2001). The case study described herein relates to a wetland restoration monitoring program in southern California that required an approach to map vegetation species composition and biophysical properties (Phinn and others 1999). Table 3 outlines the mapping and monitoring requirements and the following paragraphs describe the implementation of the framework.

Habitat Mapping in a Restored Wetland Environment

The aim of this project was to provide maps of the spatial distribution of restored vegetation cover in the low, middle and high marsh vegetation communities ofSweetwater Marsh National Wildlife Reserve, San Diego County, California, USA (Figure 2). Hence, image

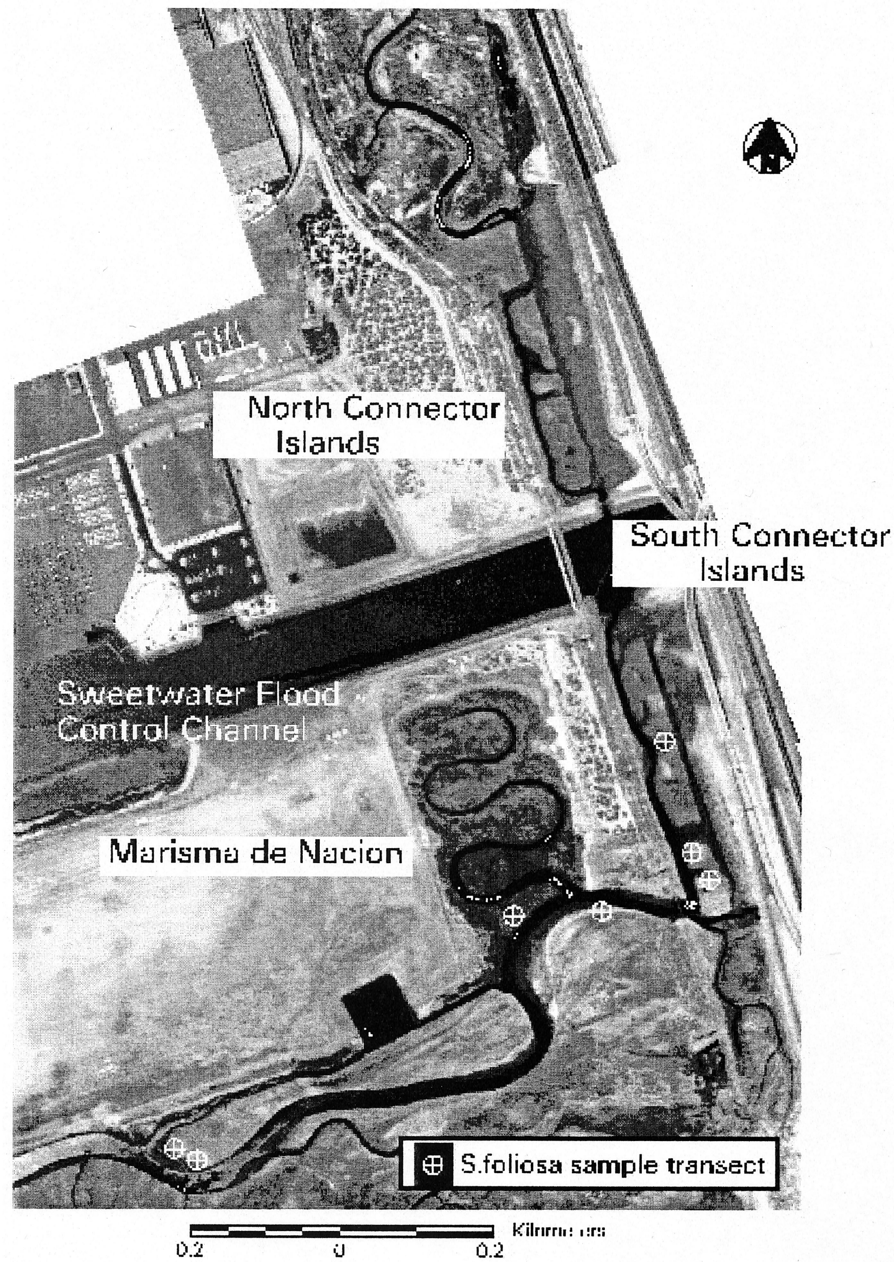

Figure 2. Location of the Sweetwater Marsh National Wildlife Reserve, San Diego County, California, USA.

data sets were required to first map the vegetation composition of the wetlands and then to estimate foliage-projective-cover (FPC) in each vegetation community. The vegetation mapping approach (Phinn and others 1999) was required to determine the condition of breeding habitat for an endangered bird species native to the saltmarshes, the light-footed clapper rail (*Rallus longirostris* ssp. *levipes*).

Input Information Requirements and Definition of the Scene Model

Prior to establishing a suitable scene model, a summary was prepared of the restoration monitoring objective, required information, and type of environment being monitored. The restoration goal was to establish a tidal wetland ecosystem capable of supporting a spec-

Table 4. Source data for spatial–temporal plot of southern California wetland structure and processes

Structure/ process	Spatial scale (length)	Temporal scale	Vegetative process	Geomorphologic process	References
Leaves, stems, roots	0.01m (leaf) 0.5m (stem)	minute days	leaf physiology and growth	not applicable	Zedler (1982), Macdonald (1988), Zedler and others (1992)
Individual plants	0.01 m (algae) 1.0 m (herb, shrub)	minute year	plant physiology and growth growth and replacement	not applicable	Zedler (1982), Mitsch and Gosselink (1993), Zedler and others (1992)
Vegetation patches	0.5 m (pickleweed) +100 m (cordgrass)	month 100 years	patch and gap dynamics dynamics secondary succession	not applicable	Zedler (1982), Macdonald (1988), Mitsch and Gosselink (1993), Zedler and others (1992)
Channel morphology	0.001 m (microrill) +100 m (channels)	minutes months years	patch and gap dynamics Secondary succession	precipitation and overland flow Tidal and flood levels sea level change	Pethick (1991), Zedler and others (1992), Mitsch and Gosselink (1993), Ferren and others (1995)
Shoreline (estuarine and oceanic)	0.01 m (height) +100 m (width)	hours months +100 years	patch and gap dynamics secondary succession	Long- and short-term wave climate Sea level change	Bloom (1983), Flick and Cayan (1984), Pethick (1991)
Wetland complex	100 m (remnant) 10 km (Pt Mugu)	hours + 1000 years	patch and gap dynamics secondary succession	shoreline position and sea level change channel morphology	Zedler (1982), Macdonald (1988), Zedler and others (1992), Ferren and others (1995)
Southern California ecoregion	100 m (smallest) +100 km (largest)	years 10^6 years	speciation, migration and extinction landscape dynamics	Climate change sea level change tectonic movement	Macdonald (1988), Zedler (1982, 1991), Zedler and others (1992)
Tides and flooding	0.01 m (shoreline) 10 km (wetland)	month years			
Herbivory	(wetland) 0.01 m (leaf)	days months			
Pathogens	100 m (patch)	days months			
Human activity	0.01 m (leaf) 100 m (patch) 0.01 m (leaf) 10 km (wetland)	days years			

ified number of breeding home ranges for the light-footed clapper rail (Zedler 1993). Assessment of the success of the project was based on delimiting patches of different marsh vegetation species to establish the areal extent and spatial distribution of high, middle, and low marsh vegetation assemblages. Horizontal FPC in each elevation zone must meet several criteria in each potential home range: (1) low marsh must contain 50% cover of pure cordgrass (*Spartina foliosa*), and have stands 90–100 m^2 with >90% cover; (2) middle marsh areas must have at least 70%; and (3) in high marsh <10% of their ground cover must come from woody species.

In the following stages, relevant literature (Table 4)

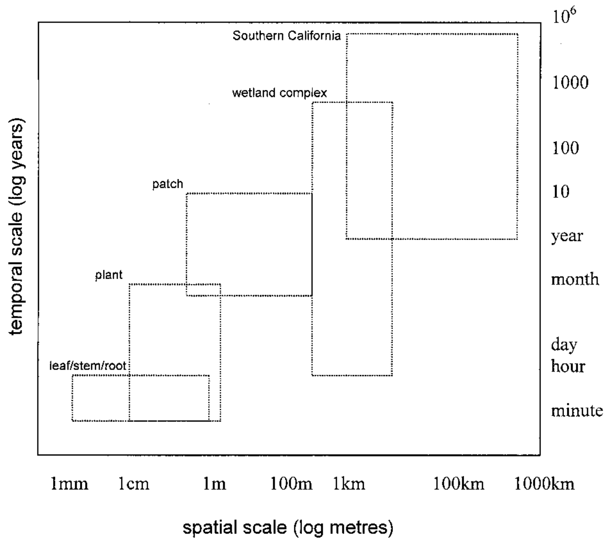

Figure 3. Spatial–temporal plot for southern California wetland structure and processes derived from Table 4.

and exploratory field and image analyses were used to identify the vegetative components of the restored wetlands environment and their hierarchical spatial ordering. The characteristic spatial dimensions for patches of low, middle, and high marsh vegetation were defined and used to estimate the ideal spatial dimensions for a remotely sensed data set that would enable the location and extent of the patches to be clearly mapped, i.e., the spatial dimensions of a scene model. Estimates of FPC were required within each of the marsh elevation–vegetation zones to assess the progress towards restoration monitoring goals. Structural differences between vegetation species common to each elevation zone required development of different models for each of the low, middle, and high marsh zones to accurately estimate FPC. Characteristic scales of structures and processes found in a restored tidal saltmarsh environment (Pacific coast, southern California) were identified from the literature (Table 4) and converted into a spatial temporal plot (Figure 3). This step represents the integration of scalar hierarchy theory with the selection of suitable remotely sensed data for the project. The spatial and temporal scales of relevant environmental structures and processes provide a basis to select image data and processing techniques at matching scales (e.g., Walker and Walker 1991).

Exploratory Spatial and Spectral Analysis of Available Remotely Sensed Data

A number of image and ground-based data sets had already been collected for the Sweetwater Marsh site, allowing an exploratory analysis to be conducted on the type(s) of information able to be extracted at multiple spatial scales (Table 5). Exploratory data analysis was based on extensive ground-based spectral–radiometric data and high-spatial resolution, multispectral image data sets collected every three months between April and October of 1993–1996. Spatial structural analyses focused on assessing the characteristic scales of features presented in Table 4. The spatial analysis techniques applied were scale-variance analysis, image classification, and semivariogram analysis. Results confirmed the spatial dimensions of saltmarsh vegetation patches and identified an optimal image pixel size for discriminating saltmarsh vegetation types. The most effective spectral bandwidths for discriminating saltmarsh vegetation communities were identified from divergence analysis (basically measuring the multivariate distances) of field located "training-sites" and variance analysis of hand-held imaging spectrometer data sets. A combination of red and near-infrared (NIR) spectral bandwidths collected from 0.75 to 2.0 m pixels were found to be most effective for discriminating different saltmarsh vegetation species.

The multitemporal nature of the image and field data also enabled the time of year at which vegetation communities were most spectrally separable to be defined. Hence, collection of image data with 1.0 m pixels using red and NIR bandwidths in the June–July period maximizes the probability of mapping the location of different saltmarsh vegetation communities. In total, the ESDA enabled verification of scene model dimensions, ensuring that the saltmarsh vegetation patches would be detectable by using the imaging dimensions specified in the scene model.

Specification and Evaluation of Suitable Remotely Sensed Data

Once exploratory analyses of the image data sets had been completed, the next stage involved comparisons of dimensions of available image data sets to those established in the scene model (Table 1). A compliance matrix (Phinn 1998) (Table 1) was then used to compare scene model dimensions to those of the candidate data set (Table 2). Each parameter of the scene model and candidate data set were evaluated and labeled as suitable, able to transform, unable to assess, or not applicable (NA). The data set with the highest suitability should then be selected as the optimal data set.

Specification of Processing and Analytical Options

The selection of an optimal image analysis approach requires consideration of the type of information required for the monitoring program and the requirements of specific analytic approaches. The restoration

Table 5. Data–lineage assessment of candidate data sets for Sweetwater Marsh restoration monitoring project

Sensor, Date	Pixel size	Spectral resolution	Geometric correction	Radiometric correction
ADAR 5000 18 Mar 92	0.52m	blue (424–494 nm) green (521–599 nm) red (620–694 nm) NIR (813–1001 nm)	band–band registration	none
1 Aug 92	0.67m	as above	band–band registration	none
4 Nov 92	0.67m	as above	band–band registration	none
3 Apr 93	0.67m	as above	band–band registration	none
1 Aug 93	0.67m	as above	band–band registration	none
1 Oct 93	0.67m	as above	band–band registration	none

monitoring program requires hardcopy and digital, georeferenced maps of FPC in high, middle, and low marsh cover type patches. A suitable technique, based on development of an empirical relationship between spectral and ground data was selected from the inventory tables (Phinn 1997), with consideration of the five criteria listed in the section above on selection of spatial analytic techniques.

Output Information

To enable delivery of the required monitoring information the final output specifications set out the presentation and storage medium to be used, established an accurate processing lineage and documented potential error sources and magnitudes. Output data were provided in hard- and soft-copy formats, as thematic maps for the restoration site indicating estimated vegetation cover and residual error levels, with tabular summaries of errors in estimates when compared to field data points. Estimates were also provided of error sources and means to quantify these where possible, e.g., band to band spatial registration <1.0 pixel and georeferencing to a base orthorectified image with an average RMSE <0.5 pixel (Phinn and others 1996). The empirical model relating spectral response to FPC also has error in the model fit to the data set used. An overall measure of the model's accuracy is provided by the adjusted r^2 value, while each cover estimate is accompanied by a residual error level. In addition to a cover map, a map of residual error estimates may also be plotted.

Framework Results Versus Ad-Hoc Solution

The framework was applied to the restoration monitoring problem after a completed project had selected an image data set and processing technique (Phinn and others 1996). This provided a more 'ad-hoc' solution to which the results of applying the framework were compared. A number of differences were obtained by using the framework to select a suitably scaled image data set and processing technique (Table 6). However, the most significant differences were obtained from the resulting image classification operations where data were selected based on application of the framework and the processing technique provided a somewhat higher overall adjusted map accuracy (67%) than the ad-hoc solution (62%).

Conclusions and Future Applications of the Framework

The framework described provides a procedure for environmental scientists and managers to select remotely sensed data and analysis techniques to map and monitor the spatial characteristics of vegetation and landscape structures. This represents a practical application of hierarchy theory and the large body of techniques for selecting optimal scales of image data sets. The spatial dimensions of vegetation and landscape elements and their hierarchical structuring were integrated with the known spatial and temporal dimensions of the required mapping or monitoring data to produce a hierarchically structured scene model. The scene model contains specifications for the spatial, spectral, and radiometric resolutions of an image data set that will enable the target feature or process to be mapped or monitored at the scale required. In developing this framework two of the fundamental problems encountered when analyzing landscape structure from remotely sensed data have been addressed. In the first case, the landscape's spatial structure is recognized and incorporated into the design and execution of the analysis. Second, a means is provided to ensure that the data collected and information from analyses of these data are at the appropriate scale and format to answer questions being asked of them. Hence the framework may serve as a heuristic tool for selecting appropriate remotely

Table 6. Image data sets and analysis techniques selected for Sweetwater Marsh monitoring with and without applying the framework

Scene model	Nonframework	Uncertainty	Framework	Uncertainty
Spatial		Implicit focus on cover types; use finest resolution available		Spatial scale info on target environment used to define scene model
H/L Resolutin	H resolution		H resolution	
Grain	0.72 m		0.72 m	
Extent	3140 × 1570 m		3140 × 1570 m	
Spectral		Use spectral bands with finest spatial resolution data		Reliability of spectrometer data 1994–95, covered all vegetation types and sample times
No. bands	4		2	
Band widths	blue 400–480 nm green 460–570 nm red 610–680 nm NIR 780–1000 nm NIR 780–1000 nm		red 610–680 nm NIR 780–100 nm NDVI	
Radiometric		As above		As above
Quantitation	0.0003 R_L		0.0003 R_L	
Dynamic Range	green 0.04 R_L red 0.07 R_L NIR 0.14 R_L		green 0.04 R_L red 0.07 R_L NIR 0.14 R_L	
Temporal		Date selection based on preliminary studies and Atlantic/Gulf coast work		Sample date based on 1994–95 spectrometer data; solar + tidal acquisition times based on field experience
Date	10 June 1995		10 June 1995	
Solar geometry	11.45 am (DST)		11.45 am (DST)	
Tidal conditions	+1.5 ft rising		+1.5 ft rising	

sensed data and analytic techniques for specific project and type of environment.

Previous applications of the framework to environmental monitoring problems illustrated several key findings. The first was related to the application of an objective mechanism in the framework to identify relevant aspects of the monitoring problem and environmental characteristics for selecting remotely sensed data and analysis techniques. This may be particularly useful when the monitoring is carried out in compliance with a legal mandate (e.g. endangered species protection). Secondly, the selection of remotely sensed data and analysis technique(s) was driven explicitly by information requirements and the spatial and temporal characteristics of the environment in question. Additional advantages of the framework were that it:

- defined the environmental monitoring problem more explicitly to enable linkage with suitable data/analysis techniques;
- provided a means to standardize the type and form of dimensions of remotely sensed data required for a project by defining dimensions of the scene model; and
- served as a heuristic tool for defining the dimensions of remotely sensed data required for a monitoring problem.

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