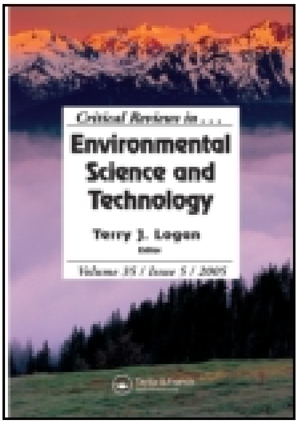

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Remote Sensing of Vegetation Pattern and Condition to Monitor Changes in Everglades Biogeochemistry

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Remote Sensing of Vegetation Pattern and Condition to Monitor Changes in Everglades Biogeochemistry

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Ground-based studies of biogeochemistry and vegetation patterning yield process understanding, but the amount of information gained by ground-based studies can be greatly enhanced by efficient, synoptic, and temporally resolute monitoring afforded by remote sensing. The variety of presently available Everglades vegetation maps reflects both the wide range of application requirements and the need to balance cost and capability. More effort needs to be applied to documenting and understanding vegetation distribution and condition as indicators of biogeochemistry and contamination. Ground-based and remote sensing studies should be modified to maximize their synergy and utility for adaptive management.

KEYWORDS: biogeochemistry, remote sensing, vegetation pattern

1 INTRODUCTION

The distribution and condition of Everglades vegetation reflect factors that affect biogeochemical cycling: climate, surface water flow, depth of flooding, duration of soil saturation, salinity, nutrients, and natural disturbances.[1] But the conversion of carbon, nitrogen (N), phosphorous (P), and other inorganic elements of the soil, atmosphere, and hydrosphere into the organic substances of plants and their release back into the environment are also influenced by human activities.[2] Restoration actions outlined in the Comprehensive Everglades Restoration Plan (CERP)[3] are aimed at modifying timing,

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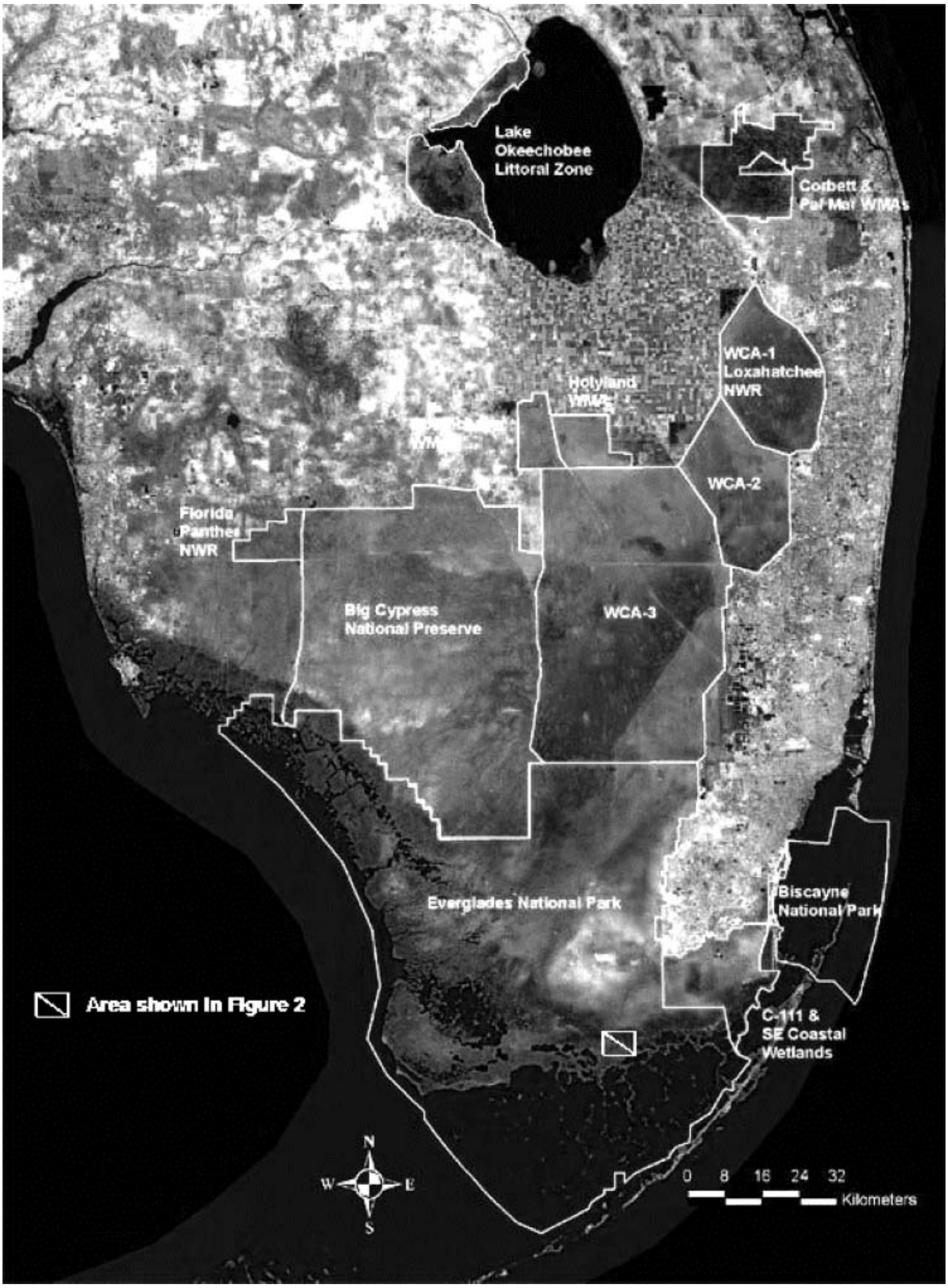

FIGURE 1. A Landsat satellite image of the greater Everglades ecosystem region with major Water Conservation Areas (WCA) and parks labeled.

quantity, and chemical composition of water flowing through the greater Everglades region (Figure 1). The goal is to influence vegetation composition, distribution, and condition to restore and preserve habitat for threatened, endangered, and other wildlife species[4] while providing flood protection and supplying water to adjacent urban and agricultural areas. Particular changes in vegetation due to the alteration of Everglades biogeochemical cycling and contaminant levels are indicators of ecosystem health and serve as restoration endpoints. Cost-effective capabilities for comprehensively characterizing landscape-scale changes in vegetation pattern help managers understand, forecast, and modify the impacts of actions such as flow regime change, decompartmentalization, and nutrient reduction on the greater Everglades system.

The objectives of this review are to synthesize past remote sensing-based studies of Everglades vegetation, identify gaps in remote sensing research that must be filled to provide restoration-critical data or understanding, and lay a foundation for further remote sensing research and applications that may benefit Everglades biogeochemical research, monitoring, and restoration. First, important concepts are defined to provide a framework for the review. Then, a brief accounting of some recent field-plot and transect-based studies of Everglades vegetation is provided because such studies are primary sources of conceptual understanding regarding vegetation/biochemistry relationships and serve as the ground-based link for remote sensing. An overview of Everglades vegetation mapping using remote sensing is also presented, recognizing that vegetation maps are a primary source of vegetation pattern information and given that, as with other models of reality, map construction requires trade-offs that affect utility and also place bounds on the information that can be drawn from them. Much of the remote sensing literature is focused on development and capability of remote sensing to measure vegetation, not on vegetation patterns themselves. Research regarding application of remote sensing to Everglades vegetation characterization is evaluated before the few cases in which remote sensing has been applied to Everglades vegetation modeling and biogeochemistry research are described. Throughout, challenges to greater use of remote sensing technologies in the Everglades are identified. Finally, the relevance of remote sensing of vegetation pattern to restoration, near- and long-term research and monitoring needs, and as an indicator of restoration success are addressed.

2 FRAMEWORK

2.1 Scope

For the purpose of this review, *remote sensing* is defined as collection, storage, and analysis of images of land surface phenomena using devices mounted on airborne and satellite platforms. Remote sensing described herein is based on instruments that make use of transmission, absorption, reflection, and emission characteristics of electromagnetic radiation from visible through microwave wavelengths (i.e., approximately 350 nm–100 cm). The Everglades Restoration Coordination and Verification (RECOVER) remote sensing subgroup identified three broad system-wide arenas to which remote sensing technology might contribute: Vegetation, Water Quality, and Hydrology.[5] Their stated goal for the vegetation arena is to quantify, monitor, and predict changes in the extent, orientation, and distribution of the vegetation communities and individual species to local, regional, and system-wide hydrologic alterations.[5] Although progress has been made in the development of remote sensing techniques to directly map changes in Everglades inundation patterns[5–7] and depth or flow direction,[8–10] primary emphasis here is placed on the characterization of coastal and inland vegetation patterns as indicators of water and soil nutrient levels and hydroperiod.

2.2 Vegetation Pattern

Here, the term *vegetation pattern* encompasses the spatial configuration of two factors: vegetation distribution and vegetation condition. *Distribution* refers to presence of vegetation (as opposed to other land covers such as open water or bare soil) and may include vegetation composition present at a location (e.g., single-species identification, identification of associations of vegetation, enumeration of within community species abundance). *Condition* refers to factors that vary within species or association, such as productivity, leaf area, biomass, or structure (e.g., height, density, ratio of woody to leaf material). Characterization of vegetation pattern includes measurement of variations through time as well as across space. Within the context of individual remote sensing studies, a clear distinction between distribution (as defined here) and condition is not typically made. Both aspects of vegetation patterning may or may not be addressed and the consideration of temporal as well as spatial patterning may or may not be of concern. But this distinction provides a useful construct for the examination of vegetation pattern through remote sensing for biogeochemical analysis.

2.3 Extent, Precision, and Resolution

Extent refers to area or length of time covered by the remote sensed data. The greatest extent possible may seem a logical goal, but it is practically constrained by costs of data collection, storage, and processing. One approach to low cost and high efficiency is the use of sample-based methods in which replicates of relatively small areas are selected and interpreted for inference to broader area conditions. In contrast, comprehensive or wall-to-wall mapping of a vegetation characteristic over an entire spatial domain is more costly but eliminates the need to extrapolate results to or make inferences about a larger area. *Precision* refers to the specificity of classification scheme into which remote measured vegetation characteristics are grouped. Another approach to lower cost or gain efficiency is to select a classification scheme that is either very generalized (e.g., lumping all vegetation into a single class)

TABLE 1. A snapshot of USGS Everglades Priority Ecosystems Study image data holdings

Sensor	# of image dates	Spectral bands	Nominal spatial resolution (m)
Airborne	variable	1/3/4	0.10–2
LiDAR	2	2	1
HYMAP/AVIRIS	2	180/226	4/17
RADARSAT	4	1	> 6.25
ERS	10	1	15
PALSAR	4	4	15
SPOT	9	4	10 / 20
AVIRIS	1	226	18
Landsat ETM+	18	9	15 / 30 / 60
Landsat TM	157	7	30 / 120
Landsat MSS	4	4	79
AVHRR (composite)	460	5	1000

Note. The variety of temporal, spectral, and spatial resolutions are being used to explore the information content provided by the various systems and resolutions. Extents for data from some systems (e.g., HYMAP) are for sample areas only whereas coverage is system-wide for others (e.g., Landsat, AVHRR).

or very narrow in scope (e.g., identification of the presence of one species). This limits the number of factors that must be considered during interpretation, in some cases to match what can be most easily extracted from the imagery—thereby requiring fewer interpretation resources. *Resolution* refers to how fine spatial, spectral, or temporal measurements are made (Table 1). Each time remote sensing is applied to the investigation of vegetation patterns these three different aspects (i.e., extent, precision, and resolution) are manipulated to balance available funding, time, and analytical resources against applications requirements.

3 SELECT GROUND-BASED STUDES OF VEGETATION PATTERN

A brief accounting of recent ground-based plot and transect studies illustrates the influence that changes in biogeochemical fluxes have on Everglades vegetation patterning. It also supports the use of vegetation mapping as an Everglades restoration performance measure and highlights spatial and temporal variability that both challenges and makes necessary the use of remote sensing. Transect studies are of particular interest here. They can be placed to provide information along gradients and typically cover larger distances than plot studies. With modification they are most appropriate for comparison against remote sensed vegetation pattern.

The influence of increased levels of Phosphorus (P) on vegetation pattern in the naturally oligotrophic Everglades has been extensively documented.[11–12] To specifically test the hypothesis that changes in P concentration are leading to changes in vegetation community, and more specifically to replacement of sawgrass (*Cladium jamaicense*) and white lily (*Nymphea* *odorata*) by cattail (*Typha domingensis* Pers.), Doren et al.[6] used a transect sampling approach. Soil nutrient and community composition data were collected in Water Conservation Area (WCA) 1, WCA-2, WCA-3 and Everglades National Park (ENP; Figure 1). Transect lengths varied between 6 and 26 km. At collection sites spaced between 0.5 and 1 km apart along each transect, a 10 m long sampling transect was placed in a sawgrass, slough, or cattail community when found there. Both P concentrations and cattail presence were negatively correlated with distance to canals, whereas a positive correlation was exhibited for the abundance of sawgrass and other naturally occurring communities. A decade later, Childers et al.[7] repeated these measurements and added vegetation stem and biomass sampling along extensions of the same transects. In locations where P enrichment had been indicated as impacting composition previously (i.e., WCA-1 and WCA-2), cattail expansion and replacement of sawgrass had occurred with even greater distance from canal sources.[7] Elevated biomass levels in sawgrass and wet prairie communities were noted at points along the ENP transect where elevated soil P concentrations were measured.[7] In contrast, along the WCA-3 transect where water impoundment along the southern margin receives little canal influence, no change in composition was exhibited. In another study, using hierarchical, nested spatial sampling in WCA-2, King et al.[8] found that P was the only environmental variable linked to patterns of coarse-scale composition, whereas nutrient (P, Nitrogen [N], and Sodium [Na]) availability and frequency of dryness were independently linked to patterns in fine-scale vegetation composition and also explained a majority of the spatial structure of undisturbed zones. All three P gradient experiments document a transition in drivers of vegetation composition and condition with distance from P influx, from enrichment near the source to fluctuations in hydrology at further distances. Hagerthey et al.[9] also documented Cladium to Typha compositional shifts along P enrichment gradients, but distinguish them from a different response to P enrichment within slough regimes, where rapid transition through a series of compositional changes takes place once critical soil and surface water P thresholds have been surpassed.

WCA-3 has recently been an area of intense study. Following an interannual analysis of community composition there, Powers[10] coined the term *meta-stable communities* to describe the high within-community annual variation resulting from seasonal and annual changes in weather and water flow. Zweig and Kitchens[11] suggested that present-day communities are different than those previously described at the landscape scale[12] and reflect an altered, wetter hydrology. And, whereas community level response depends on the characteristics of hydrologic changes, ecology and life-history traits make some individual species better indicators of or either short-term or long-term shifts.[11] Zweig and Kitchens[11] suggested that sawgrass should be monitored for long-term change over periods of years, whereas changes in spike rush (*Eleocharis spp.*) location and structure are indicative of shorter term (e.g., intra- or interannual) hydrologic fluctuations. Similar to others (e.g., King et al.[11]; Ewe et al.[13]; Givnish et al.[14]), Zweig and Kitchens[11] stressed the unknown, potential importance of other environmental factors on vegetation patterning and suggest that continued monitoring is needed to increase understanding of wetland dynamics and ecology. Through a multi-decadal study of transect-based vegetation sampling in the ENP, Armentano et al.[15] compared vegetation composition repeatedly sampled along five ENP transects from 1980 to 1997 against simulated water levels and reached conclusions similar to Zweig and Kitchens'[11] analysis in WCA-3: vegetation communities can respond to altered hydrology rapidly, for example within a four-year period.

Other landscape factors affecting WCA-3 patterning were explicitly examined by Givnish et al.[14] through field study and conceptual model development. They attributed tree island composition and condition to top predator-induced concentration of P at tree island heads and the characteristic teardrop shape of these tree islands downstream of the head to the redistribution of this P by water flow. This landscape-based conceptual model of tree island patterning is an alternative to the groundwater-flux based explanation of P redistribution proposed by Ross et al.[16] in which very high evapotranspiration rates and associated P fluxes are suggested as the mechanism for P redistribution and tree island shape. With regard to vegetation dynamics, Givnish et al.[14] concluded that WCA-3 vegetation at the time of their evaluation had not yet reached equilibrium with recent changes in water management. Regions of very different hydroperiod and water depth were occupied by similar communities that typically respond to changes in water depth and flow over periods of months to years.[14]

Recent studies suggest that changes in the condition of vegetation (without changes in vegetation composition) are evident in some important Everglades species over even shorter time scales and may provide earlier indications of soil nutrient enrichment. For example, although their sampling frequency was insufficient to measure seasonal or high or low flow events that may drive seasonal changes in productivity of producers like periphyton, Ewe et al.[13] did observe interannual differences in sawgrass productivity. And through dosing experiments, Smith et al.[17] recorded structural changes in sawgrass at levels lower than those associated with conversion of community composition from sawgrass to cattail—suggesting that the monitoring of vegetation condition affords more advanced notice of potentially important changes.

This brief review of field-based studies shows that patterns of vegetation composition and structure reflect the complex interaction of biogeochemical, water flow, and also other biological factors (not discussed here), such as seed dispersal, fire, and invasive species. Everglades vegetation distribution and condition are temporally variable and are likely not in equilibrium with an environment that continues to change with alteration of water management practices (among other factors). Although they yield critical insights regarding factors that influence community composition and habitat pattern, field studies can be costly and difficult to perform over the long term or over large areas, particularly with a goal of minimizing impact on the fragile Everglades environment. Remote sensing is by no means a substitute for field studies. Fine-scale changes that can be measured on the ground can go undetected through remote sensing for some time, that is, until changes affect large areas. But remote sensing can provide the context needed to plan the most effective and efficient smaller scale, finer resolution field studies. Remote sensing can also provide information on the distribution of and relationships among biogeochemical cycles and vegetation at broad scales that cannot be discerned through field studies alone. When the logistic challenges associated with field survey, the complexity of factors affecting vegetation patterning, and the high temporal variability of vegetation are considered together, incentive for the development and application of remote-sensing techniques to detect and monitor changes in vegetation composition and structure is multiplied.

4 EVERGLADES VEGETATION MAPPING OVERVIEW

Remote sensing initially served as input to narratives regarding vegetation distribution. Some of this early work was not spatially explicit and therefore difficult to use for comparisons with conditions at present. For example, Davis's[18] vegetation map was derived from black-and-white aerial photos collected in 1940, but comparison with more recent mapping efforts has shown that he grouped broad ranges of vegetation together, that analyses were not quantified or documentable as to location,[19] and that prominent map features such as forested tree islands bear no geographic correspondence with other vegetation maps.[20] Johnson[21] used aerial photographs solely to illustrate the spread of bushy vegetation in the ENP without tying his interpreted maps to particular location or scale. And although Loveless[12] relied in part on inputs of airborne photographic data, he produced no maps as part of his foundational description of Everglades vegetation. Kolopinski and Higer[22] published one of the first spatially explicit vegetation maps for three community types using samples of imagery from 1940, 1952, and 1960. McPherson[23] mapped vegetation communities at five sites using 1940 and 1972 air photos. Air photos or very high spatial resolution satellite data have since been used to produce various other vegetation maps for subareas of the Everglades[19,24–26] sometimes with a focus on particular species such as invasive *Meleleuca quinquenervia*[27–28] or *Lygodium microphyllum*.[29] In mapping vegetation along transects within the ENP from 1973 winter color infrared (CIR) photos, Olmsted and Armentano[19] documented some of the air photo interpretation difficulties presented by Everglades vegetation mapping, noting difficulty distinguishing spike rush from sawgrass due to variable reflection of periphyton, the assemblage of algae and bacteria that forms on the substrate and on plants in the Everglades.[30] Cattail could not be seen in the photographs and are only indicated on their maps where it was encountered on the ground.[19]

An emphasis on greater Everglades ecosystem modeling and monitoring created even greater need for system-wide information on vegetation distribution and condition. Regional mapping efforts were undertaken by the U.S. Fish and Wildlife National Wetland Inventory,[31] the U.S. Geological Survey (USGS) Gap Analysis Program,[32] the Florida Department of Transportation,[33] and a collaboration by the National Park Service (NPS), the South Florida Water Management District (SFWMD), and the University of Georgia (UGA).[40–42] Estimates of predrainage vegetation patterns have also been assembled from previous air photo and satellite interpretations and Government Land Office records.[34] Differences among the maps produced reflect their different intended purposes and the need to balance cost of production against extent, precision, and resolution. Although other large-area maps were put to such purposes, the NPS, UGA, and SFWMD mapping effort produced the first large-area map of Everglades vegetation composition intended for vegetation characterization and analysis at the community or individual species level.[20] It established an important vegetation distribution baseline, but shares a trait common to all Everglades vegetation maps: no individual product can meet every restoration science need. Specifications such as the minimum mapping unit, its classification scheme, and the air photo interpretation key associated with the system have been well described.[31–33] Although the protocol produces relatively accurate species and community identifications, it is not well suited for mapping variation in condition (e.g., structure by our definition) within species or community class (Figure 2). Automated classifications offer the potential for numerical exploitation of subtle differences in surface reflectance often caused by differences in vegetation structure or condition that would be difficult, if not impossible to map through visual interpretation alone. For example, Carter et al.[35] produced a map of vegetation flow resistance classes through statistical processing of multispectral Thematic Mapper data (to include thermal emission). At 30 m spatial resolution (or minimum mapping unit), they distinguished various densities and structures of vegetation that were not adequately represented by other visual mapping techniques. As with every other example, the resulting map product meets the demands of the purpose for which it was created (flow resistance indexing for hydrodynamic modeling). However, the structure-based vegetation groupings used in the Carter map limit the data's utility for other ecosystems applications. To provide baseline vegetation composition data for CERP, a hybrid approach that relies on visual interpretation of color infrared photography through analytical stereo plotters has been developed.[36] A restoration-focused classification scheme[37] identifies dominant

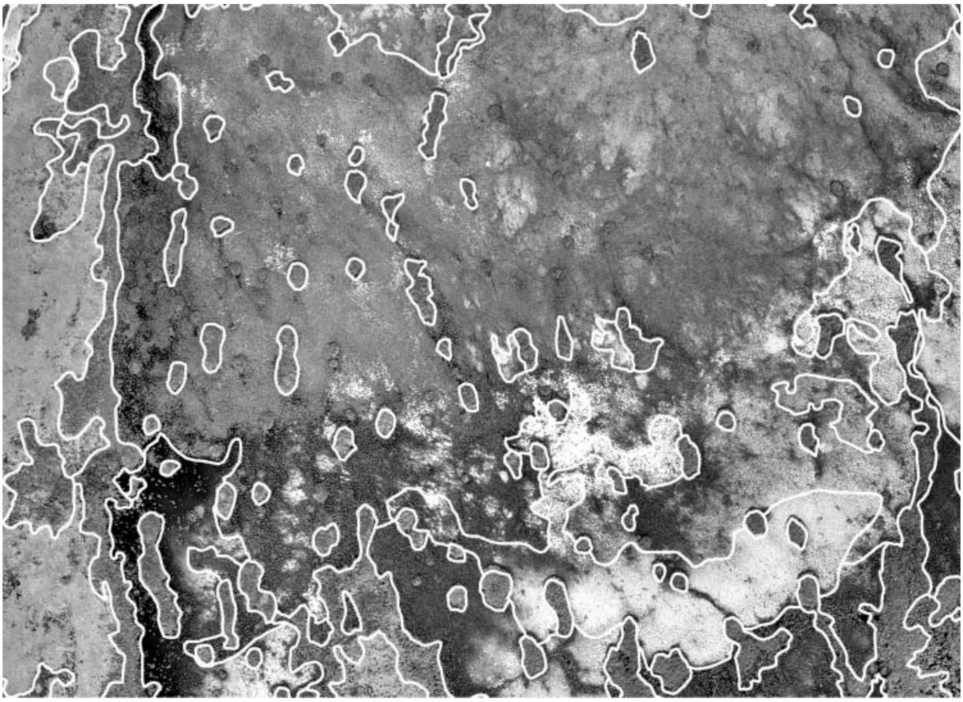

FIGURE 2. Hand-delineated vegetation polygons over their source imagery. Minimum mapping unit, classification scheme, and subjectivity preclude mapping of variations in vegetation condition useful for ecotone monitoring and processed-based modeling. The combination of manual (composition) and automated (condition) measurements may meet more restoration needs.

and secondary vegetation communities and these community assignments are made to areas of $\frac{1}{4}$ hectare in size based on established protocols for photointerpretation.

Continued methods research is showing that when both high spatial and high spectral resolution data are collected, automated mapping of individual (and particular) vegetation species with adequate accuracy may be feasible. Hyperspectral imaging systems are those that simultaneously collect a hundred or more measurements in narrow bands across the electromagnetic spectrum to afford the examination of absorption features for material identification.[38] This technology has been used widely in mineral identification[39] and shows promise for leaf biochemistry,[40–42] but exploitation of increased spectral data for plant study in the Everglades environment is not simple and early efforts to distinguish Red, Black, and White mangrove species using airborne high spectral resolution measurements were unsuccessful.[43] More recently, Hirano et al.[44] processed airborne hyperspectral imagery to map vegetation composition over the southern end of the ENP (Figure 1). The overall accuracy of their vegetation maps was only moderate (i.e., 66% correct). However, because invasive species were particularly evident, they asserted that hyperspectral remote sensing is suitable for invasive species identification that is difficult to accomplish through visual interpretation alone. This is supported by the work of Lass and Prather,[45] who found that pure pixels of Brazilian Pepper (*Schinus terebinthifolius*) could be located in 5 m spatial resolution hyperspectral imagery. And, by combining pure signatures of Pepper with that of other vegetation types, both monotypic and mixtures of Pepper and other land cover types may be identified. This is an example in which spectral information is exploited to estimate subminimum mapping unit mixtures of vegetation composition not possible through visual interpretation. The tendency for invasives (and cattail) to form large patches of monotypic stands likely aids their discrimination from native communities through remote sensing. Others have shown that individual species and mixture mapping is difficult where Everglades plant heterogeneity is high. Using high spatial resolution but low spectral resolution data, both Wu and Rutchey[29] and Fuller[27] found mixed vegetation to be a source of confusion for automated classifiers. A pilot study conducted under contract with the U.S. Corps of Engineers and SFWMD further north in Florida (i.e., the Kissimmee watershed restoration project) examined utility of airborne hyperspectral remote sensing for vegetation mapping[46] and demonstrated typical facets of remote sensed vegetation map accuracy. When 12 broad-vegetation groups were the objective and good ground-based data existed to develop the data processing model, accuracy was high (e.g., 89% of test points were correctly classified). However, when classes for which little training data exist were included in the accuracy assessment performance was lower (i.e., 65% correctly classified). And, for a map with finer vegetation associations (68 classes rather then 12), the percentage correctly classified dropped to 70% and 35% for well and poorly trained classifications, respectively.[46] Automated techniques afforded by digital processing of hyperspectral imagery are attractive for their subjectivity and speed of execution. However, results are highly reliant on good ground-based training data and performance is closely tied to the target vegetation classification scheme. And, because area of coverage is reduced to balance the cost of increased spectral and spatial resolution provided by such hyperspectral sensors, to date they have only been employed for sample-based methods development over relatively small areas. The increased use of hyperspectral remote sensing can be expected with reduced costs given greater availability of high-capacity hyperspectral sensing systems and improved accuracy through advances in automated image analysis techniques.

Given their continued development and wider availability, active remote sensing systems such as Light Detection and Ranging (LiDAR) and Radio Detection and Ranging (RADAR) are being applied to Everglades vegetation characterization. Proisy et al.[47] explored the promise of polarimetric RADAR for monitoring mangrove vegetation condition. They found that return and biomass statistical relationships must be restricted to homogeneous closed canopies because of water substrate impacts on returns—once again highlighting some of the challenges to remote sensing posed by this wetlands system. Air- and spaceborne LiDAR measurements of canopy height have been used to calibrate and evaluate space-based RADAR data to estimate mangrove height[48] and standing biomass[49] in the Everglades and wetlands of Colombia, South America. Height estimates were more accurate in taller stature forests (i.e., in Colombia) where clear views of the water substrate through the canopy were not as common. But in both cases, model performance depended on the accuracy of calibration data extracted from the LiDAR and field-measured canopy characteristics. Houle et al.[50] used object-oriented analysis to segment a 2 km × 500 m LiDAR image of the ENP into broad land cover classes of marsh, pine forest, and hammock, and to characterize the structure of the canopy and subcanopy within those communities. Although transition zones between adjacent pine forests and hammocks and within-class height statistics could be generated, classification was hampered by poor ground conditions that limited access to all areas, again demonstrating the reliance of remote sensing techniques on high-quality ground-based sampling.[50] Though these efforts yield promising results for the prospect of vegetation condition mapping, they are typical in that a great deal of remote sensing research related to vegetation in the Florida Everglades (and elsewhere) has focused on mapping methods and vegetation characterization without applying the technology to fully document and gain insights regarding causes for the vegetation patterns themselves.

5 EVERGLADES VEGETATION PATTERN FROM REMOTE SENSING

5.1 Vegetation Distribution

Early remote-sensing-based investigations of vegetation change were sample-based, conducted in ENP, and focused on impacts of water management. For example, Kolopinski and Higer[22] attributed measured decreases in wet prairie communities and increases in sawgrass marsh and woody vegetation, interpreted from over one dozen square-mile plots of Shark Valley Slough, to trends toward shortened hydroperiods, increases in fire, and loss of soil following extensive dry down. McPherson[23] made vegetation models for five sites in WCA-3 from panchromatic air photos acquired in 1940 and 1970. He attributed observed declines in tree island health, measured reduction in tree island extent, and flourishing emergent marsh vegetation on tree islands at southern and southeastern sites to impoundment and rainfall induced increases in water depth and hydroperiod.

Starting in the mid-1990s several efforts were undertaken to comprehensively track vegetation change for larger areas of the Everglades. Differences in cattail abundance and biomass in WCA-2 were recognized in air photos and described through field experiment by Chiang et al.[51] Similar to their field-based counterparts, this remote detection and documentation of the distribution and condition of cattail along P gradients illustrates the linkage between vegetation pattern and biogeochemistry. These remote-sensing studies relied on sophisticated quantitative analyses of vegetation distribution and condition, afforded through the input of digital vegetation data into Geographic Information System (GIS) technology. Jensen et al.[52] used automated processing of several satellite image types to map distribution of cattail, among other vegetation communities in WCA-2, over a multidecadal time period. This effort has become one of the most often cited works on wetland vegetation change due to changes in nutrient and other biochemical fluxes.[53] Subsequent reanalysis of those data also highlighted challenges to remote sensing that are posed by the Everglades environment. Through comparison with vegetation data interpreted from aerial photography, Rutchey and Vilcheck[54] found that Jensen et al.'s[52] satellite-based maps, when used as a baseline, overestimate cattail expansion and attribute this to difficulties associated with satellite-based remote sensing of Everglades vegetation: variable hydrology (depth and color) of the substrate, transient impacts from fire and periphyton composition, and similarities in macrophyte growth morphology (e.g., among sawgrass and cattail). Although some of these challenges remain in manually interpreted airborne remote sensing,[19,27] interpreters can painstakingly bring multiple factors to bear (termed *convergence of evidence*) to identify vegetation at the species level through stereo image viewing.

GIS technology has enabled more sophisticated study of vegetation distribution. For example, the WCA-2 digital vegetation data from Jensen et al.[52] were progressively spatially resampled from 20 to 1000 m, and used to calculate cover fraction, fractal, and diversity indices by Obeysekera and Rutchey.[55] Results show that important landscape features such as tree islands and brush mixture communities nearly disappear at scale lengths beyond 700 m and area–perimeter relationships change rapidly above 100 m.[55] This suggests that a resolution of approximately 50 m (1/4 hectare—the minimum mapping unit employed in present vegetation mapping) is required to capture important vegetation patterns through remote sensing. Brandt et al.[56] used stratified random sampling to select WCA-1 study sites and map margins of tree islands greater than 100 m^2 in area from digital scans of winter air photographs collected in 1950 and 1990–1991. GIS-measured shape, size, and configuration of the tree islands were analyzed for changes across the study time period. A tendency toward fewer, smaller, irregularly shaped tree islands were attributed to alterations of hydrology for WCA-1.[56] In the modern equivalent of McPherson's[23] sample based study in WCA-3, total number and acres of tree islands in WCA-3 were interpreted from 1940, 1952–1954, 1972–1973, 1980, and 1994–1995, and compared against the latest comprehensive vegetation map product.[36] Results showed that impoundment has caused significant loss of tree island habitat and establishment of large expanses of cattail adjacent to and downstream of inflow structures. With air photos as input, Wu et al.[57] used landscape indices of spatial complexity to detect thresholds for deteriorating or deteriorated patterns of ridges and sloughs and describe how such metrics may prove useful for both scientific forecasts and management evaluation of flow restoration alternatives.

5.2 Vegetation Condition

Remote sensing of Everglades vegetation condition (e.g., biomass, structure) is typically focused on particular vegetation growth forms and intended to explore the documentation of vegetation condition without particular emphasis on causes for changes in condition, other than event-driven disturbance. For example, most Everglades vegetation condition research using remote sensing has focused on mangrove forests and on forest response to disturbance. An air-photo-based classification of mangrove die-off, notable for its reliance on shape and size of die off patches as well as final morphology of dead trees, was suggested by Finn et al.[58] for use in restoration monitoring. Additional application of this system is not reflected in the literature, but routine collection of very high-resolution imagery and improved computer processing of shape and configuration data may allow similar monitoring to occur. Zhang[59] analyzed airborne LiDAR imagery to characterize the density, size distribution, and formation rate of mangrove forest gaps caused by lightning strikes. Although failing to distinguish among mangrove species using airborne collected spectra, Ramsey and Jenson[43] did find a relationship between canopy structure (leaf area index or LAI specifically) and a basic vegetation index (the widely used normalized difference vegetation index or NDVI). In a study on the Florida Keys, Davis and Jensen[60] found high correlations among other vegetation indices derived from high spatial resolution (2.5 m) airborne imagery and measures of mangrove LAI and percent cover, and also slightly lower correlations with diameter at breast height or canopy height. Moderate resolution satellite imagery has also been employed for mangrove biophysical study. Jensen et al.[61] found strong correlations among vegetation indices derived from 20 m spatial resolution SPOT and canopy closure and maximum canopy height.

The few examples of remote sensed analyses of marsh vegetation condition have been motivated by the need to add vegetation parameters to hydrodynamic models. Using airborne video imagery of ground-based vegetation sampling areas[62–63] to model sawgrass density, Anderson[64] found that amount of variation in measured sawgrass explained by the remote sensing based model was dependent on the target study area's water depth. Once again the importance of the highly variable Everglades vegetation substrate is indicated. Those airborne and field data were also reanalyzed (Figure 3) in

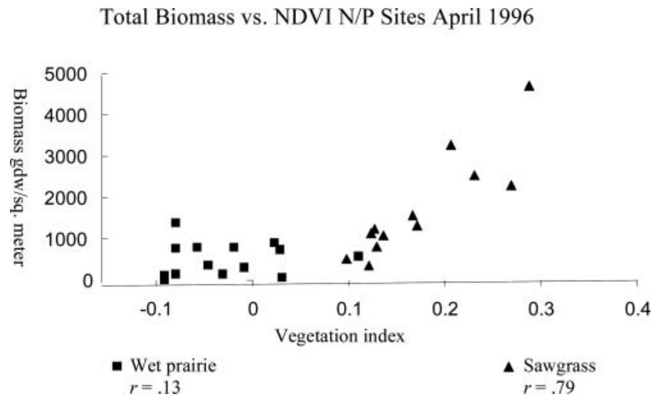

FIGURE 3. Relationships among field-collected total biomass (including periphyton) and a vegetation index derived from airborne multispectral imagery show strong relationships in moderate density sawgrass ridge (triangles) and no relationship in wet prairie (squares) sites (adapted from Jones[65]).

an effort to extrapolate density and biomass relationships to larger areas using wall-to-wall airborne color infrared and multispectral satellite imagery.[65] As part of this research, geostatistical analysis of vegetation index data derived from 1 m airborne color infrared suggested that the 30 m resolution of Landsat Thematic Mapper imagery was appropriate to capture the average spatial scale lengths of vegetation density variation (indexed through NDVI) across the Everglades region.[65] This supported the use of satellite imagery for vegetation condition mapping as input to regional hydrodynamic models.

5.3 Periphyton and Foliar Chemistry

Although vegetation condition reflects or influences biogeochemistry, remote sensing of vegetation condition has only just begun to be explicitly tied to biogeochemical cycling in the Everglades. The general influence of chemical composition on narrow wavelength light reflection and absorption by soils, plants, and water on has been the object of remote sensing research elsewhere.[38,69] Field-based collection of Everglades leaf, canopy, and other surfaces that would be imaged remotely has been underway.[70] Periphyton species composition is a relatively rapid indicator of P enrichment[14,30,71,72] and affects mercury methylation.[73–74] Ground- and image-based reflectance spectroscopy of Everglades algal and bacterial matt chemical composition along P gradients suggests that hyperspectral remote sensing (or imaging spectroscopy) shows promise for contaminant and other biogeochemical monitoring in the Everglades.[75] After examining some of these spectra, Rivero et al.[76] compared vegetation metrics derived from one scene each of Landsat Enhanced Thematic Mapper and Advanced Spaceborne Thermal Emission and Reflection Radiometer satellite imagery for two different dates to soil and floc total P (TP) in WCA-2A. Given the influence of P on periphyton and macrophyte production a traditional remote sensed vegetation metric's sensitivity to *Chlorophll A* was found to be most effective in predicting floc TP. Rivero et al.[76] also concluded that remote sensing data can be combined with limited soil and water samples to improve the spatial resolution of soil and water chemical composition maps. To date, logistical challenges, the relatively high cost of data acquisition, the complexity associated with digital remote sensing analysis, highly variable atmosphere and substrates, and a lack of established methods have all combined to limit research that links airplane and satellite based image metrics to biogeochemistry through periphyton and other vegetation dynamics. However, given the recent trend toward no-cost (to the user) satellite data distribution,[77] data cost and availability for these types of research and monitoring are becoming less of an obstacle.

5.3 Modeling Vegetation Pattern

There are some examples of the use of remote sensed vegetation information for dynamic vegetation model development and evaluation in regions where biogeochemical gradients have been documented.[22,59–61] Wu et al. used the vegetation distribution maps produced by Jensen et al. as the actual landscape in calculating transition probabilities for a model of cattail spread in WCA-2.[67] The original vegetation classes were recast into two groups, unimpacted natural vegetation (sawgrass) and impacted anthropogenic vegetation (cattail). Rare events (very dry periods) were included to account for cattail spread to nonadjacent sawgrass areas. Once information on biogeochemistry was added, the model explained and confirmed much of what we know about the cattail invasion of the Everglades (e.g., the role of arenchyma tissue and rhizomes).[67] Although shortcomings of the input vegetation data were later recognized,[54] their use in estimating average invasion rates, changes in landscape patchiness, and changes in transition rates through time is notable. Wu et al.[29] used IKONOS satellite data to map the invasive *Lygodium microphyllum* in WCA-1 and compare its recent distribution with that documented previously by Richardson et al.[68] This analysis showed that Lygodium is likely to establish on the southeast side of a tree island and spread to the northwest as a reflection of prevailing winds in south Florida. Richardson et al.[68] also estimated its future rate of spread based their change analysis.[29] Greater development of dynamic models of land cover, and vegetation in particular, is needed to better understand the rates of vegetation change, the linkages among vegetation distribution and condition, and environmental factors such as contaminants and the effectiveness treatment measures. Multidate remote sensing studies can contribute to these objectives.

6 RESTORATION RELEVANCE AND FUTURE DIRECTIONS

The objectives of the Everglades restoration are to get the water right; restore, preserve, and protect natural habitats and species; and foster compatibility between the built and natural systems.[78] To accomplish these objectives as efficiently and effectively as possible, vegetation responses to changes in biogeochemistry and flow must be monitored in a timely fashion. Additionally, the need to forecast system response to planned and potential changes requires greater understanding of linkages among biogeochemistry and vegetation pattern. Ground-based approaches continue to yield critical information on pattern-process relationships. But the sample-based approach field-based studies require may not provide the coverage necessary to adequately document ecotone variations at landscape scales in changing environments. These factors combine to suggest that the application of present and pursuit of new remote-sensing techniques, products, and understanding are warranted. The baseline on regional vegetation distribution created by comprehensive vegetation mapping is critical to the monitoring of impacts of restoration actions on vegetation pattern and habitat. This baseline should be extended through repeat mapping cycles. But wall-to-wall mapping of this type on the time scale suggested by community composition changes witnessed through field work (i.e., at $\frac{1}{2}$ decade intervals) would be difficult for the long term. Remote sensing techniques that provide spatially continuous and frequent information on vegetation condition are needed to monitor, model, and forecast system behavior in the face of change. The following sections address the information needs that must be met to make progress in using remote sensing to link vegetation pattern to biogeochemistry for the benefit of Everglades restoration and adaptive management.

6.1 Near-Term Information Needs

Two aspects of Everglades vegetation study can be immediately exercised to improve remote sensing of biogeochemical cycles and contaminants as well as better inform restoration science and adaptive management. First, existing ground-based datasets should be extensively documented and openly shared with the remote sensing community to facilitate their use in remote sensed vegetation pattern study. This may make maximum use of information from both types of endeavors and inform future data collection missions. Second, a great deal of research has been conducted on the development of remote sensing methods to characterize Everglades vegetation, although less has been applied to documenting and understanding the vegetation patterns these techniques can measure. Researchers should capitalize on the considerable effort expended to date on vegetation mapping by mining existing data for information on relationships among vegetation pattern and biogeochemistry.

6.2 Long-Term Monitoring and Modeling Needs

Over the mid- to long term, more research is needed to increase synergy among ground-based sampling activities and remote sensing missions. Field data-collection protocols that allow aggregation at levels meaningful for comparison against airborne and satellite-based measurements should also be developed. In previous studies, the placement of sample sites has often been based on subjective criteria (sometimes with the aid of airborne imagery) to provide representative information on community composition or structure.[7,15,62–63] Also, too few measurements have been made at small sample areas (e.g., 10 m long transects)[7,15] to allow scaling of ground data to moderate resolution satellite data with sufficient statistical power. Good examples of statistically valid, regional sampling approaches exist.[79] But more that are specifically tailored to remote sensed data calibration are needed to make maximum use of the increasing number of remote-sensed images available for the Everglades. Creative ways have been found to process ground-based digital imagery for rapid, nondestructive vegetation assessment (e.g., Childers et al.[71]). But recent, more widespread access to Global Positioning System (GPS), inexpensive and high-resolution digital photography, and GIS are creating a perfect storm for the exchange of information and linkage of field and remote-sensed data that may help satisfy long-term needs. As part of their transect-based field study, Givnish et al.[14] processed vegetation index data from high-resolution airborne imagery of their sampling sites. This is an example of field collection of biophysical information with near-coincident airborne imagery that lends to scaling studies using airborne and satellite imagery. Running et al.[80] provided the logic for a global vegetation classification scheme that is relevant for the enhancement of Everglades field data collection. Researchers should seek simple field measurements on observable, unambiguous characteristics of vegetation structure that are important to ecosystem biogeochemistry and retrievable from remote-sensed imagery. Vegetation classes that directly translate into the biophysical parameters of interest to modeling communities need to be developed.

The ability to understand rates, causes, and consequences of land cover change is critical to development of models to forecast future land cover states.[81] Long-term data are essential for characterizing temporal dynamics of ecological and hydrological processes and determining critical ecosystem thresholds.[82] Long-term datasets have been used to correct misconceptions based on shorter windows of data, identify the cyclic nature of some ecohydrological dynamics, and aid in the recognition of extreme, rare, and common events.[83] It is notable that most of the air-photo-based remote-sensing studies described[18,22,28,36,54,56,64] made use of winter imagery only. Seasonal variations among vegetation have not been exploited. Greater focus should be placed on teasing intra- and interannual variations in Everglades vegetation productivity from the available satellite record. Collectively constituting the largest consistent satellite database available for natural resource management at present[84–85] the Landsat archive has been proposed for retrospective assessment of rangeland environments.[86] This archive's utility for Everglades retrospective analysis should be more fully investigated. Analysis of variation in vegetation biomass using high spatial resolution, airborne imagery suggests that average spatial scale lengths for vegetation variation may be characterized with Landsat Thematic Mapper data.[65] If rapid changes in vegetation distribution or condition can be detected through automated processing of operational satellite data, more labor-intensive, high-resolution visual change analysis could be focused on identified areas of change on an as-needed basis. Other aspects of vegetation dynamics can also be investigated using operational satellite systems. For example, although restoration efforts to date have focused on modification of water flow and timing, the interactions between fire, hydrology, and vegetation must also be better understood and communicated if restoration and management are to be fully successful.[87]

The technology for remotely sensed data collection has also diversified, giving rise to new remote sensing platforms with increased temporal resolution, increased spectral resolution and range, and less dependence on optimal light and weather conditions (i.e., active sensing systems such as RADAR and LiDAR). In addition, digital image processing and classification technologies continue to develop at a rapid pace. Change detection techniques[89] have progressed far beyond simple differencing of categorical maps of land cover to sophisticated analysis of multitemporal spectra. Object-oriented techniques[90] make use of spatial as well as spectral information in remote sensed imagery. Nonparametric classifiers such as classification trees[91] allow categorical and ratio-scale data to be stacked and analyzed simultaneously. These are just a few examples of many approaches designed to capitalize on increasing availability of fine resolution, hyperspectral, and multivariate datasets that should be examined for their potential in characterizing Everglades vegetation and biogeochemistry. Although research regarding the information content of imagery from these new sensors has been conducted (e.g., Sano et al.[88]) more research of this type is needed in the Everglades and similar wetland environments. Simply stated, the information content, relative to vegetation distribution and condition, of various satellite systems needs to be explored.

Previously highlighted challenges for Everglades remote sensing, such as heterogeneous land cover, highly variable substrates, and a humid subtropical atmosphere are particularly problematic for the application of spaceborne optical remote sensing. Difficulty achieving adequate classification accuracy for trend analyses has prevented widespread adoption of satellite based systems for monitoring of Everglades vegetation composition. The accuracy of land cover data has been a primary occupation of the remote sensing community as a whole. Yet, proper accuracy assessment and determination of minimum accuracy requirements remain sources of controversy that impede its widespread use.[92] Collection protocols and stringent accuracy requirements for regional-scale maps of Everglades vegetation composition from visual interpretation of airborne imagery have been developed with due consideration of restoration needs and data collection costs.[36,37,93] The promise of spaceborne systems for monitoring vegetation condition and other indicators of biogeochemical fluxes remains given advances in systems capabilities, sensor calibration, and processing algorithms. But before this promise can be realized and meaningful analyses of temporal variations in vegetation and biogeochemistry can be made, additional creativity is needed regarding assessment techniques, metrics, and thresholds for accuracy. Particular emphasis should be placed on the accuracy required to monitor changes in vegetation condition and patterning from space as well as the affects of individual vegetation composition map accuracies on change detection and trend analyses.

6.3 Relevance as an Indicator of Success

If the legislated reduction of P concentrations in Everglades surface water is obtained, will it succeed in producing the desired impact on vegetation composition? Will changes in sheetflow caused by decompartmentalization have the desired beneficial effect on ridge and slough patterning? Because restoration is aimed at modifying hydrology, water and soil chemistry, and vegetation to improve habitat, vegetation pattern is a highly relevant indicator of our ability to reach restoration objectives. Planning tools such as performance measures are being used to determine the degree to which implemented plans and proposed alternatives achieve or are likely achieve, respectively, the goals and objectives of the CERP. A suite of measures related to wetland landscape patterns (Table 2) have been developed and will be adapted and modified as additional scientific information becomes available.[94] Remote sensing can likely meet the measure of restoration success offered by Armentano et al.[15]: although typical wetland restoration focuses on species diversity within communities, for the Everglades the diversity of communities themselves is a key objective. In contrast, Sklar et al.[95] proposed the use of complexity indices that rely on measures of species diversity, basal area, stem density, and canopy height in their specification of tree island restoration objectives. Operational remote sensing to track a performance metric such as this requires continued development and fusion of field and remote sensing technologies. Regardless, any point along the spectrum of complexity for indicators of success would benefit from the ability remote sensing provides to synoptically and efficiently monitor vegetation pattern transformation in near real time.

TABLE 2. Examples of various approved and proposed performance measures to which remote sensing might directly (D) or indirectly (I) contribute meaningful data

Subarea	Measure	Technology	D or I
Wetland landscape patterns	Freshwater & Estuarine Vegetation Mosaics	ALL	D
Wetland landscape patterns	Marl Prairie Cape Sable Sparrow	Hi-spatial resolution	D
Wetland landscape patterns	Ridge & Slough Community Sustainability	ALL	D
Wetland landscape patterns	Tidal Creek Sustainability	Hi-spatial resolution	D
Greater Everglades Wetlands	Inundation patterns	MSS & RADAR	D
Greater Everglades Wetlands	Extreme high & low water	RADAR	D
Greater Everglades Wetlands	Surface water TP concentrations	ALL	I

Note. ALL = multiple systems are capable of providing pertinent measurements (although for some variables, the fusion of data from multiple systems may be required); MSS = multispectral satellite or airborne imagery.

7 CONCLUSIONS

Decades of Everglades science have developed a base of literature connecting vegetation distribution and condition to biogeochemistry, water fluxes, and other factors. Much of this work has been based on analysis of point or transect data collected over small subregional scales. But the Greater Everglades Ecosystem is large and complex. And many of the changes that indicate degradation or loss of function in a natural system such as the Everglades start subtly and occur at scales that challenge conventional thinking.[85] To meet the demands of Everglades restoration, tools to measure and understand the impacts of actions such as flow regime changes, decompartmentalization, and nutrient reduction on the greater Everglades system are needed. Cost-effective capabilities for comprehensively characterizing landscape-scale changes in vegetation pattern must be developed. Remote sensing and geospatial processing technologies provide efficient and nondestructive means of synoptically monitoring relationships among vegetation, biogeochemical cycles, resource use, and other biological factors at multiple scales. To be successfully employed in the Everglades, remote sensing needs to focus more on analysis of vegetation patterning and changes in condition through time rather than development of remote sensing methods alone. To that end, complimentary ground-based sampling protocols must be developed and implemented. The content of freely available archival satellite data must be mined for information on spatial and temporal dynamics of vegetation composition and condition, and multiple sensing technologies must be fused and leveraged. Finally, the information and understanding these efforts will create must be applied to the development and application of models that forecast system behavior in the face of natural and anthropogenic change.

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