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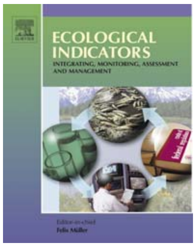

# Phytoplankton bloom status: Chlorophyll *a* biomass as an indicator of water quality condition in the southern estuaries of Florida, USA

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ABSTRACT

Altered freshwater inflows have affected circulation, salinity, and water quality patterns of Florida Bay, in turn altering the structure and function of this estuary. Changes in water quality and salinity and associated loss of dense turtle grass and other submerged aquatic vegetation (SAV) in Florida Bay have created a condition in the bay where sediments and nutrients have been regularly disturbed, frequently causing large and dense phytoplankton blooms. These algal and cyanobacterial blooms in turn often cause further loss of more recently established SAV, exacerbating the conditions causing the blooms. Chlorophyll *a* (CHLA) was selected as an indicator of water quality because it is an indicator of phytoplankton biomass, with concentrations reflecting the integrated effect of many of the water quality factors that may be altered by restoration activities. Overall, we assessed the CHLA indicator as being (1) relevant and reflecting the state of the Florida Bay ecosystem, (2) sensitive to ecosystem drivers (stressors, especially nutrient loading), (3) feasible to monitor, and (4) scientifically defensible. Distinct zones within the bay were defined according to statistical and consensual information. Threshold levels of CHLA for each zone were defined using historical data and scientific consensus. A presentation template of condition of the bay using these thresholds is shown as an example of an outreach product.

## 1. Introduction and background

There is a long history of the application of chlorophyll *a* (CHLA) as an index of the productivity and trophic condition of estuaries, coastal and oceanic waters. Initially, Steele (1962) summarized the application of CHLA as an indicator of photoautotrophic biomass as related to primary productivity. Cullen (1982) further addressed the use of CHLA as an index for biomass of primary producers. CHLA biomass reflects the net result (standing stock) of both growth and loss processes in pelagic waters. CHLA is considered the principal variable to use as a trophic state indicator. There is generally a good agreement between planktonic primary production and algal biomass, and algal biomass is an excellent trophic state indicator. Furthermore, algal biomass is associated with the visible symptoms of eutrophication, and it is usually the cause of the practical problems resulting from eutrophication. CHLA is relatively easy to measure compared to algal biomass. One serious weakness of the use of chlorophyll a is the great variability of cellular chlorophyll content (0.1–9.7% of fresh

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algal weight) depending on algal species. A great variability in individual cases can be expected, either seasonally or on an annual basis due to a species composition, light conditions and nutrient availability.

Phytoplankton blooms, commonly called algal blooms (although cyanobacteria can be the dominant constituent), are a major concern in both Florida Bay and the nearshore waters of the Florida Keys and southwest Florida coast (Rudnick et al., 2005). Phytoplankton blooms decrease light penetration through the water column and can depress seagrass growth and productivity. Seagrass decomposition along with the subsequent destabilization of the sediments can lead to the release of nutrients and in turn stimulate more phytoplankton growth. This potential positive feedback loop (Rudnick et al., 2005; Zieman et al., 1999) underscores the importance of monitoring and modeling phytoplankton blooms, as well as conducting research on the processes regulating bloom inception, maintenance, and termination (Florida Bay PMC, 2004; CERP RECOVER MAP, 2004). That nutrients from the Everglades are causing Florida Bay phytoplankton blooms has not been proven, but correlative analysis of prior blooms has suggested these inputs are an important factor and that increased fresh water flows (with similar nutrient loads) would increase such blooms (Brand, 2002; CROGEE, 2002). It is important to consider phytoplankton blooms in the southern estuaries as an indicator of restoration success both because blooms could significantly harm these estuaries and adjacent coastal systems, and because they occur at the terminus of the entire Kissimmee–Okeechobee–Everglades ecosystem. The dependence of estuarine water quality on watershed flows could constrain upstream activities throughout the entire ecosystem. Ensuring the health of the terminal module of this integrated ecosystem provides assurance that we ‘‘got it right’’ and properly restored a sufficient portion of the upstream ecosystem to assure sustainability. Therefore, one of the restoration goals established in the Comprehensive Everglades Restoration Program (CERP) is to minimize the magnitude, duration, and spatial extent of phytoplankton blooms that can adversely affect light penetration and thus the sustainability of healthy and productive seagrass habitat.

The cause of phytoplankton blooms may in fact vary both temporally and spatially in the southern estuaries. Fresh water discharges with associated nutrients from the Everglades is a contributing factor to phytoplankton bloom initiation, and sustenance in this region. On the SW Florida Shelf and in western Florida Bay, a significant correlation has also been found between upstream flow rates and diatom biomass (Jurado et al., 2007). Runoff from the Everglades watershed to the SW Florida Shelf has also been implicated as the nutrient source which allowed the highly publicized Blackwater event of 2003, an ecologically damaging phytoplankton bloom, to persist and be transported into the Florida Keys National Marine Sanctuary (Hu et al., 2002). Most recently, a persistent phytoplankton bloom began in the fall of 2005 in Barnes Sound, Manatee Bay, and Blackwater Sound; three embayments with high residence times in northeastern Florida Bay and southern Biscayne Bay. The initiation of this bloom is believed to be the result of an interaction between local road construction activities and hurricane-related disturbance, which included an intentional freshwater release from the C-111 canal for flood control prior to the passage of Hurricane Katrina (Rudnick et al., 2006). This canal discharge increased total phosphorous (TP) loading of Manatee Bay.

These observations, as well as the aforementioned correlative analysis of historical blooms, have highlighted the importance of water column CHLA concentration as a parameter that should continue to be monitored within the CERP Monitoring and Assessment Plan to ensure that water quality in the southern estuaries is not degraded by CERP implementation. A CERP objective is to avoid having a highly oligotrophic system transformed into a eutrophic ecosystem with decreased sea grass cover and a diminished extent of the high quality benthic nursery habitat necessary to support commercial and recreational fisheries.

### 1.1. *CERP monitoring and assessment plan (MAP) hypotheses related to phytoplankton blooms*

The spatial extent, duration, density, and composition of phytoplankton blooms are controlled by several factors that will be influenced by CERP. These include:

- external nutrient loading;
- internal nutrient cycling (seagrass productivity/die-off, sediment resuspension);
- light availability (e.g. modified by sediment resuspension and dissolved organic matter);
- water residence time;
- grazing by zooplankton and benthic filter feeders.

Through modification of the quantity, quality, timing, and distribution of freshwater, CERP implementation will affect dissolved and particulate nutrients delivered to the estuaries and alter estuarine water quality. These modifications will affect primary production and food webs in estuaries. These modifications include:

- Changes in the distribution and timing of nutrient inputs through increased flow via Shark River Slough and diversion of canal flows from a ‘point source’ to more ‘diffuse’ delivery through coastal wetlands and creeks.
- Changes in the quantity of nutrient inputs to the estuaries through alteration in the mobilization and release of nutrients from developed and agricultural areas, through nutrient uptake in storm treatment areas, and through changes in nutrient processing and retention in the Everglades.
- Changes in the bioavailability of nutrients, which depends on the quality of nutrients (e.g. watershed inorganic nutrients versus dissolved organic matter (DOM) and the chemical composition of this DOM, and internal estuarine mechanisms (e.g. P limitation of DOM decomposition).
- Internal nutrient cycling rates (e.g., nitrogen fixation and denitrification) and biogeochemical processes, such as phosphate adsorption, will change with CERP implementation because of salinity and benthic habitat changes.

- Nutrient accumulation and retention in estuaries is affected by episodic storm events, which can export nutrient-rich sediments. CERP implementation will modify benthic habitats and nutrient loading, which will affect this export.

### 1.2. *Areas of the everglades covered by this indicator*

This indicator is specific to the southern estuaries including Florida Bay, Florida's largest estuary (see Fig. 1). However, the indicator is equally applicable to the assessment of CERP effects upon the other estuaries and coastal systems of South Florida. The influence of land use and watershed management on the water quality of these downstream systems is of general concern to restoration managers, policy makers, and the South Florida public, which is concentrated along the coast.

### 1.3. *Indicator history*

Extensive monitoring and research in the Florida Bay ecosystem has documented long-term water quality trends and elucidated the dynamics of phytoplankton blooms (Boyer et al., 1999; Boyer and Briceño, 2006; Boyer and Keller, 2007; Hitchcock et al., 2007). Studies have demonstrated that these blooms are limited in the eastern bay by the availability of P, but that blooms in the western bay are more influenced by the

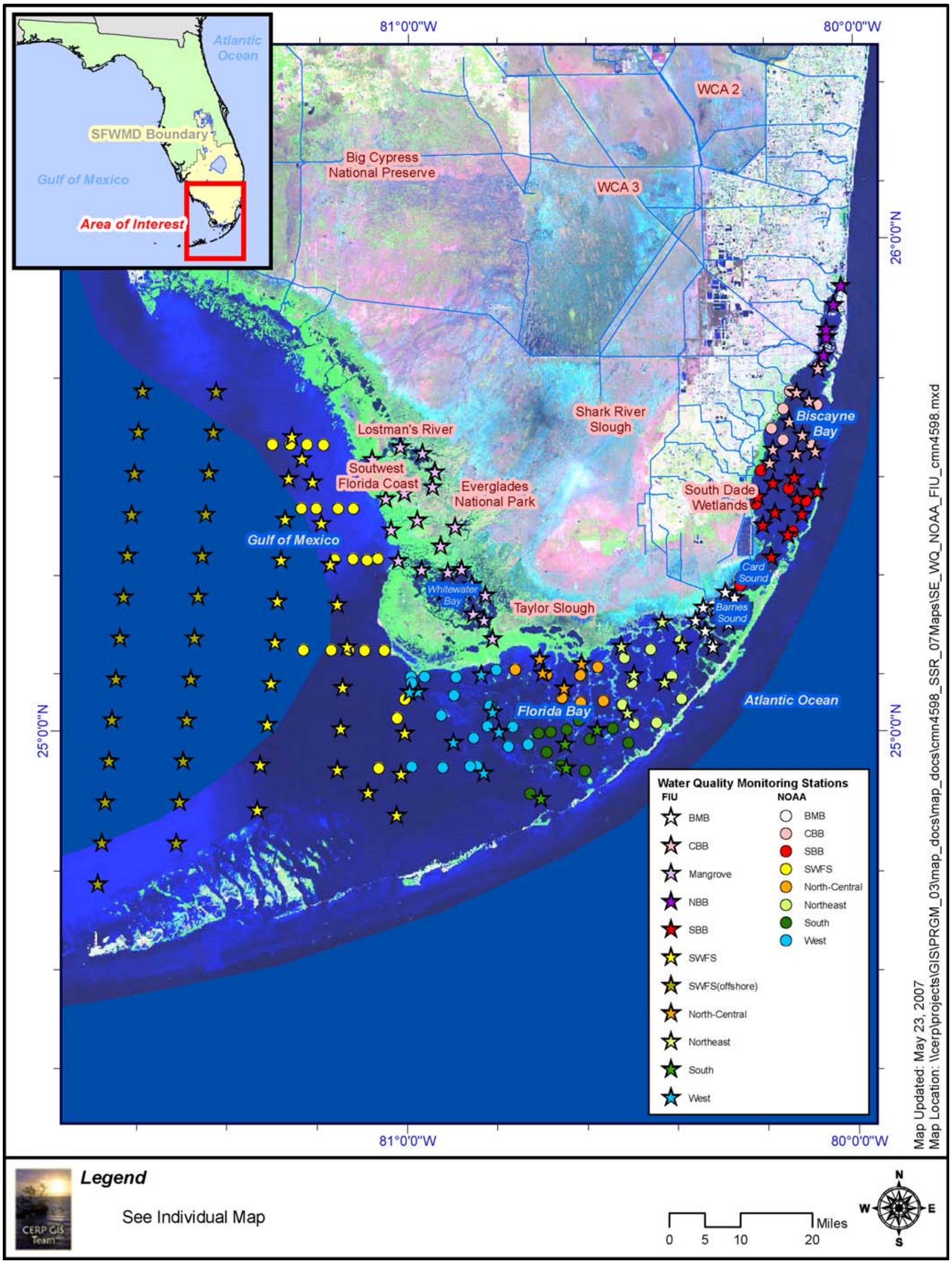


**Fig. 1 – Map depicting NOAA/AOML's and FIU/SERC fixed water quality sampling stations in the southern estuaries.**

availability of N (Fourqurean et al., 1993; Tomas et al., 1999). Studies also suggest that grazing by sponges is capable of influencing the magnitude of phytoplankton blooms (Peterson et al., 2006).

A nutrient loading budget of Florida Bay indicated that while the Everglades is a minor source of P, it is a more significant source of N (Rudnick et al., 1999). However, most of this N is bound in organic compounds and its importance to phytoplankton bloom formation or maintenance will depend upon rates at which these compounds become available by decomposition into inorganic nutrients, upon the relative inputs of other nitrogen sources, and upon the rates of internal cycling (Boyer and Keller, 2007; Rudnick et al., 2005). All of these processes are subjects of ongoing research (see Boyer and Keller, 2007; Hitchcock et al., 2007 for details). Other studies have highlighted the importance of hydrological dynamics and salinity variability (Childers et al., 2006). Perhaps most importantly, nutrient availability is influenced by nutrient exchange between sediment and water – a consequence of the shallow water depth and seagrass dominance characteristic of Florida Bay (Zhang et al., 2004; Yarbro and Carlson, 2008).

The initiation of phytoplankton blooms in Florida Bay in 1991, following the seagrass mass-mortality event of the late 1980s, has been a major element of ecological change (Fourqurean and Robblee, 1999; Rudnick et al., 2005). Since 1991, prolonged blooms (at least seasonal in duration) have been common in the central and western bay, with CHLA values frequently exceeding 5 ppb and occasionally exceeding 10 ppb (Hitchcock et al., 2007; Boyer and Keller, 2007). The most pronounced blooms occurred in the mid-1990s (a period of high rainfall) and following a series of tropical storms (including Hurricane Irene) in late 1999 and into 2000. Potential causes of these blooms have been detailed in Hitchcock et al. (2007) and potential links to management have been discussed in several documents (CERP RECOVER MAP, 2004; Rudnick et al., 2005; Brand, 2002).

Nitrogen inputs from the Everglades, associated with freshwater flow (Rudnick et al., 1999) are a potential link between watershed management and phytoplankton blooms in Florida Bay. It has been demonstrated that phytoplankton (phytoplankton) growth in central and western Florida Bay is frequently limited by the availability of nitrogen (Tomas et al., 1999). Freshwater flow from the Everglades is known to be a major source of nitrogen for the bay (Rudnick et al., 1999). Furthermore, the amount of nitrogen flowing into the bay from this source appears to increase with increasing freshwater flow. It is not certain that the quality of this nitrogen (its ''bioavailability''), which is contained in dissolved organic compounds, is sufficient to fuel phytoplankton blooms, but a positive correlation of CHLA concentration in central Florida Bay and annual freshwater discharge has been documented (Brand, 2002). Assessment of the bioavailability of Everglades nitrogen is part of the MAP and is underway.

Evaluating cause and effect relationships, including the influence of Everglades inputs, requires research of both external sources and internal cycling, research of phytoplankton nutrient limitations and production, and ecosystem synthesis and analysis using numerical models, such as the dynamic water quality model developed as part of the CERP Florida Bay and Florida Keys Feasibility Study (FBFKFS).

## 1.4. *Significance of the indicator to everglades restoration*

### 1.4.1. *The indicator is relevant to the southern estuaries component of the greater everglades ecosystem and reflects the overall condition of the Florida bay ecosystem and adjacent waters*

Phytoplankton blooms in Florida Bay have been documented in the ecosystem since the early 1990s and may represent a shift in the state of the system from largely benthic (seagrass) production to a system where benthic production is less dominant and less stable. Phytoplankton blooms have been observed to cover large areas of the central and western bay for extended periods of time (especially during summer and fall). Phytoplankton blooms may have diminished ecosystem integrity and the abundance and sustainability of living marine resources (e.g. fish and shrimp) that depend on seagrass habitat. As noted above, assessing phytoplankton bloom condition in is essential to ensure that water quality in the southern estuaries is not degraded by CERP implementation and a highly oligotrophic system transformed into a eutrophic ecosystem with decreased sea grass cover and diminished extent of the high quality benthic nursery habitat necessary to support commercial and recreational fisheries.

### 1.4.2. *The indicator is feasible to implement and is scientifically defensible*

Water column CHLA, a proxy for phytoplankton biomass, has been monitored as part of the FIU South Florida coastal monitoring program since 1989 and by the NOAA/AOML South Florida Program since 1996, establishing a baseline against which restoration success can be gauged (Boyer et al., 1997). CHLA has been widely utilized to assess the state of aquatic ecosystems and possible human impacts (c.f. Hakanson et al., 2007; Millie et al., 2006). Research in Florida Bay has been coordinated with monitoring in such a way as to provide an understanding of many of the mechanisms that influence bloom dynamics within the bay. Moreover the observational data and process studies are being synthesized and analyzed using numerical models, from relatively simple non-spatial models of benthic–pelagic coupling (Madden et al., 2009) to a complex a water quality model of the FBFKFS. Such model analyses can help provide quantitative insights into mechanistic relationships, put into perspective the influence of past human activities, and help predict the influence of future human activities. It can be especially helpful in determining the relative effect of different causal factors with respect to specific bloom events.

### 1.4.3. *The indicator is sensitive to system drivers (Stressors)*

Phytoplankton blooms are generally known to be sensitive to nutrient inputs and the southern estuaries are no exception. In fact, the recent, dramatic phytoplankton bloom in the sounds of northeast Florida Bay and southern Biscayne Bay highlighted the sensitivity of this module to an increase in ambient TP concentrations (from approximately 0.01 ppm to 0.10 ppm), likely from Everglades, Florida Bay, and Florid Bay sources that were disturbed by hurricanes and human activities (Rudnick et al., 2006). The bloom was initiated and chlorophyll *a* increased eight-fold in response to this increase in TP concentration. This bloom's incidence and sustenance over 3 years highlights the sensitivity of the southern estuaries, which have long water residence times (Lee et al., 2008), to pulsed (short-term) nutrient enrichment events. The occurrence of the eastern Florida Bay bloom also indicates that these estuaries may be more sensitive to nutrient inputs from the Everglades than previously appreciated and more likely to be sensitive to the systematic changes expected with restoration. The restoration of freshwater flow is expected to decrease one stressor (hyper-salinity and highly variable salinity) with its deleterious impacts on seagrass communities and grazers (e.g. bivalves and sponges), which could then improve water quality (potentially with long-term decreases in phytoplankton blooms). On the other hand, this assumes that the restoration of freshwater flow does not significantly increase nutrient loading to the southern estuaries. The recent occurrence of phytoplankton blooms in eastern Florida Bay indicates that that short-term nutrient loading events can produce a significant and relatively long-lasted ecological consequence.

#### 1.4.4. *The indicator is integrative*

CHLA in the water column of Florida bay is an excellent, integrative indicator of the bay's overall water quality. CHLA responds to both macronutrient loading and availability and is thus a more sensitive and relevant indicator of water quality than nutrient concentrations per se. In addition to nutrients, this indicator integrates the effect of grazers both benthic and pelagic as well changes in turbidity associated with sediment resuspension and light extinction from turbidity and phytoplankton, which influence the sustainability of SAV habitat.

Subsequent to the sea grass die-offs and coincident with the large phytoplankton bloom in the early 1990s, Florida Bay lost a significant proportion of its sponge biomass (Butler et al., 1995). It has been proposed that this loss of sponge biomass decreased grazing pressure on phytoplankton to such a degree that it allowed for more frequent, intense and persistent phytoplankton blooms in some areas of the Bay (Peterson et al., 2006). In part due to this interaction, this indicator may to some extent also reflect the dominance of benthic versus pelagic secondary productivity and food web structure.

## 2. Methods

### 2.1. *Definition of the phytoplankton bloom indicator*

The role of nutrient inputs from the Everglades in initiating and perpetuating phytoplankton blooms in the southern estuaries is unclear and likely varies throughout the region. For CHLA to be a useful indicator of bloom status it is necessary to quantify and understand the baseline conditions for CHLA and be capable of identifying deviations from this baseline which may occur as a result of CERP. The behavior of this phytoplankton bloom indicator, is distinct throughout individual sub-regions of the southern estuaries due to differences in freshwater runoff patterns (Kelble et al., 2007; Nuttle et al., 2000), circulation (Lee et al., 2006, 2008), sediment biogeochemistry (Zhang et al., 2004), nutrient inputs (Rudnick et al., 1999), grazer biomass (Peterson et al., 2006), light attenuation (Kelble et al., 2005), and phytoplankton species composition (Phlips and Badylak, 1996). To facilitate analysis the southern estuaries domain was divided into ten sub-regions (Fig. 2) based upon statistical methodologies (Boyer et al., 1999; Caccia and Boyer, 2005) and analysis of circulation patterns (Lee et al., 2006, 2008).

The 10 sub-regions are the SW Florida Shelf (SWFS), mangrove transition zone (MTZ), west Florida Bay (WFB), north-central Florida Bay (NCFB), south Florida Bay (SFB), northeast Florida Bay (NEFB), Blackwater, Manatee, and Barnes Sounds (BMB), south Biscayne Bay (SBB), central Biscayne Bay (CBB), and north Biscayne Bay (NBB). An analysis of the data demonstrates that CHLA concentration is not normally distributed in any of these sub-regions all of which are skewed towards lower concentrations. As such, the midpoint of the data is best represented by the median and it is necessary to conduct non-parametric statistical tests to analyze the data. EPA guidelines (EPA, 2001) were applied to establish the reference conditions for CHLA concentrations and set criteria for determining what constitutes elevated levels of CHLA. Under this approach a median concentration greater than the reference conditions 75th percentile is classified as elevated from baseline. In addition, Kruskal–Wallis tests were employed to test for statistically significant differences in CHLA between 2006 and all data collected prior to 2006. If any differences were significant, more detailed analyses were undertaken to identify underlying changes in water quality parameters and determine the ultimate cause(s) of the observed change.

### 2.2. *The metrics and performance measures used to determine success*

The CHLA indicator has three specific components: bloom magnitude, bloom frequency, and bloom spatial extent as follows:

1. *Bloom magnitude*: incidence of CHLA concentrations (ppb) that exceed the baseline value per zone per month.
2. *Bloom frequency*: number of months (for field monitoring results) per year when CHLA concentrations in each zone exceed the specified threshold value for that zone.
3. *Bloom spatial extent*: area-weighted CHLA concentration within a region per month exceeding the threshold concentration for the region.

The restoration target for all three components is to minimize the indicator value. We expect that as a result of improved storm-water treatment combined with the sustained growth of seagrass and sponge beds (as a restoration response), nutrient availability and phytoplankton blooms will not increase (and may decrease) with restoration despite increasing freshwater flows.

### 2.3. *Thresholds for the phytoplankton bloom indicator*

CHLA concentrations monitored since 1989 by FIU/SFWMD (Boyer et al., 1997; Boyer and Briceño, 2007) and since 1996 by

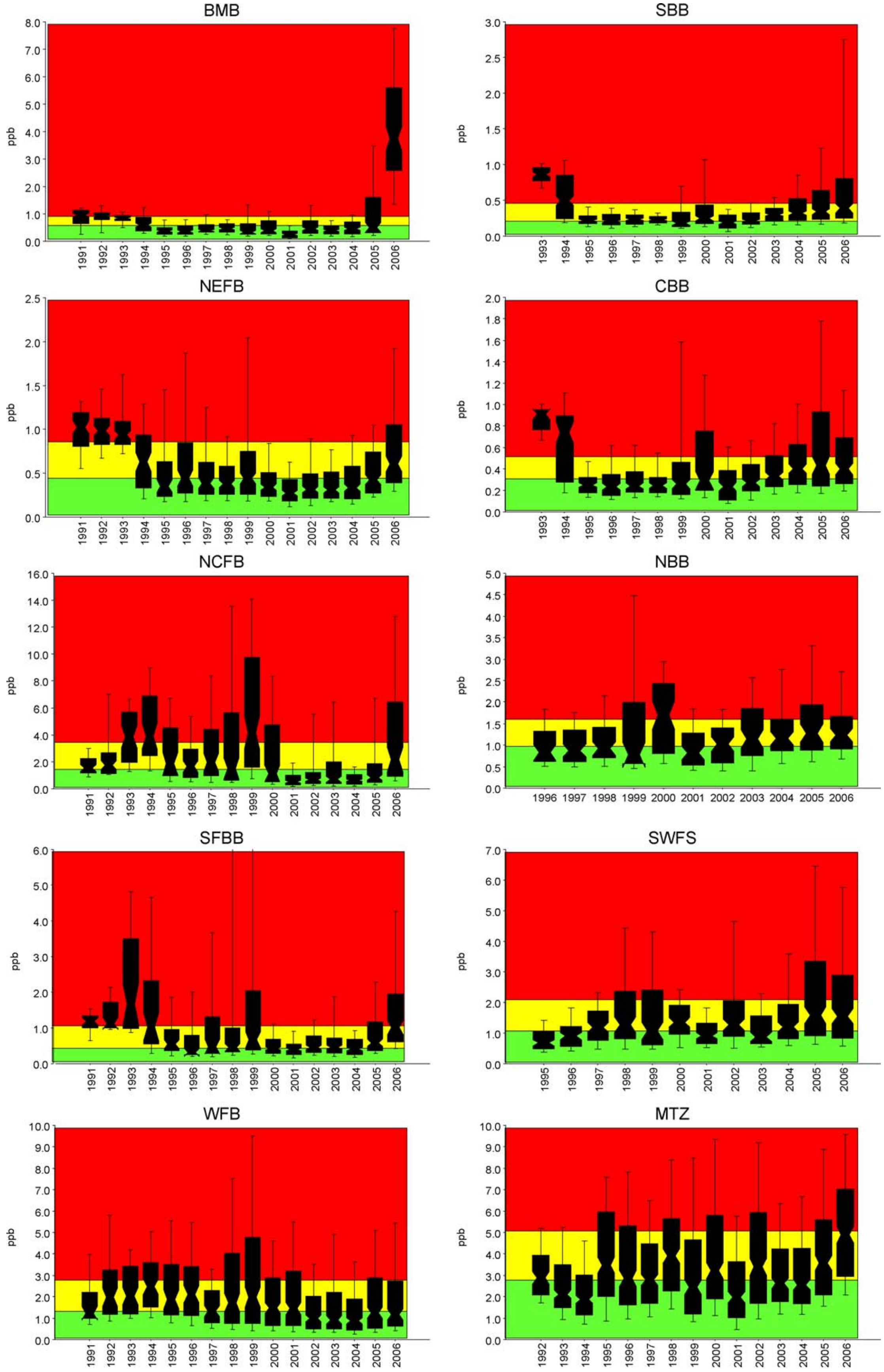


**Fig. 2 – Box and whisker plots of annual CHLA (ppb) in each sub-region. *Note* – label on SFB panel says "SFBB".**

**Table 1 – List of distinct water quality zones in Florida Bay and Biscayne Bay and their associated algal bloom thresholds as CHLA (ppb).**

| Sub-region | Zone | Valid N | 25th percentile | Median | 75th percentile |
|---|---|---|---|---|---|
| Blackwater, Manatee, Barnes Sound | BMB | 1704 | 0.306 | 0.526 | 0.910 |
| Central Biscayne Bay | CBB | 1673 | 0.200 | 0.313 | 0.566 |
| Mangrove Transition Zone | MTZ | 3803 | 1.690 | 2.863 | 4.903 |
| North Biscayne Bay | NBB | 635 | 0.670 | 1.048 | 1.648 |
| North-central Florida Bay | NCFB | 1399 | 0.585 | 1.216 | 3.710 |
| Northeast Florida Bay | NEFB | 1979 | 0.254 | 0.417 | 0.790 |
| South Biscayne Bay | SBB | 2257 | 0.181 | 0.264 | 0.426 |
| South Florida Bay | SFB | 1695 | 0.327 | 0.533 | 1.059 |
| Southwest Florida Shelf | SWFS | 1297 | 0.739 | 1.180 | 1.976 |
| West Florida Bay | WFB | 2304 | 0.653 | 1.345 | 2.845 |

NOAA/AOML, were merged and analyzed with respect to the EPA guidelines outlined above. The median and quartiles were calculated to quantify the reference conditions for the ten sub-regions of the southern estuaries (Table 1). These reference conditions were then used to establish criteria from which the status of CHLA and thus water quality in each of the sub-regions can be evaluated on an annual basis. If the annual median CHLA concentration is greater than the reference median, but lower than the 75th percentile, the sub-region is marked yellow and if the annual median concentration is greater than the 75th percentile of the reference, the sub-region is marked red. This approach yields relatively low thresholds (almost half of the sub-regions would go red at greater than 1 ppb) and regions with higher thresholds like FBNC would still go yellow at slightly over 1 ppb. The only exception is the mangrove transition zone which has a significantly higher threshold.

The data may be plotted as a series of annual box and whisker plots to provide a visual representation of the analysis including the variability in the underlying data (Fig. 2). The box and whisker plots have the median as their centerline, the 95% confidence intervals of the median as the notches in the box, the 25th and 75th percentiles demark the edges of the box and the whiskers extend to the 5th and 95th percentile. Thus, the notches and the boxes can be utilized as a pseudo-test for significant differences between medians.

## 3. Results

### 3.1. *Current status of the indicator*

From this box and whisker analysis, a stoplight map may be produced to display the current status of CHLA in each sub-region (Fig. 3). A Kruskal–Wallis test would show if there has been a significant change in median CHLA concentration over time. The additional statistical test is necessary, because a random sample will be higher than the median and thus yellow 50% of the time even if no significant change has occurred. The sub-regions which have received red ratings may be targeted for further investigation to strengthen inferences regarding the cause of the degradation in water quality, especially concerning the role of CERP versus other anthropogenic activities or natural variability. The physical environment (particularly salinity) of the shallow southern estuaries is highly responsive to tropical storms and changes in regional rainfall associated with climate variability (El Nino or Atlantic Multidecadal Oscillation). Thus, water quality and CHLA likely respond to these same natural events and it will take considerable care to demonstrate that a change is definitively due to CERP.

The 2006 analysis showed that of the 10 sub-regions 1 was green, 8 were yellow, and 1 was red (Fig. 3). Two sub-regions, the MTZ and BMB, had the highest median CHLA concentrations of any year on record. The red sub-regions include Blackwater, Manatee, and Barnes Sounds and the entire 95% confidence interval of the median is located in the red region of the graph, indicating there was a substantial increase in CHLA in this sub-region in 2006. This is an area that has been subject over the past 2 years to significant disturbances unrelated to CERP implementation. In April of 2005, a road construction project began to widen US Highway 1 in this region. This involved a significant amount of cutting and mulching of mangroves and soil tilling. Also, from August to October 2005 three hurricanes passed through the region. In addition to

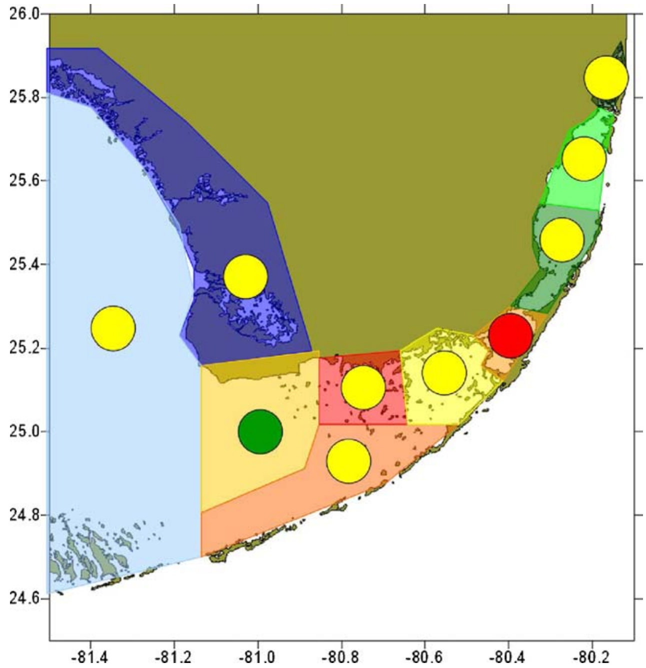
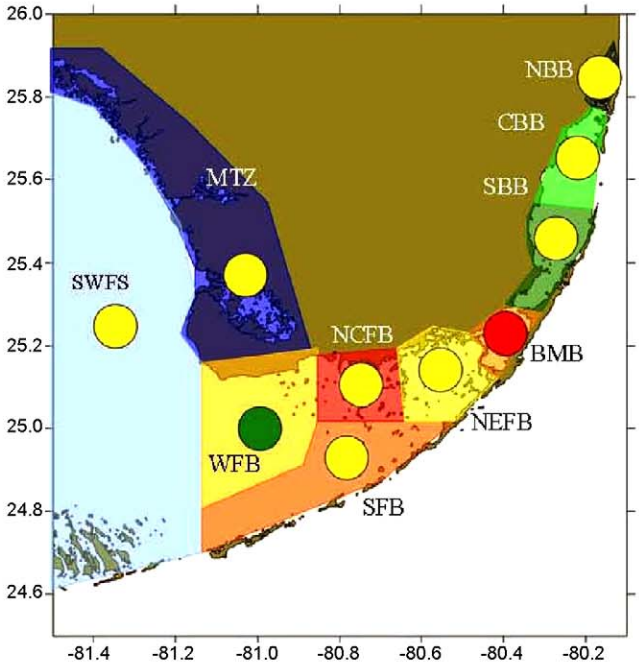


**Fig. 3 – Regional map of 2006 condition of the CHLA indicator. The circle in each sub-region displays the current status according to Stoplight criteria.**

## KEY FINDINGS – SOUTHERN ESTUARIES

**SUMMARY FINDING**: Re-suspension of nutrients from the 2005 hurricane season resulted in algal blooms in many regions of the southern estuaries and may cause continued algal blooms in the bay for some time. However, this is expected to subside within a few additional years in lieu of further significant hurricane activity and if water flows to the southern estuaries is improved should return to predominantly green for all regions with the possible exception of BMB. If water flows do not improve the areas will probably remain yellow.



Map of Florida Bay regions with stoplight ratings by region

**KEY FINDINGS:**

1. The majority of regions assessed had significant algal bloom activity that appears to have been predominantly influenced by the heavy 2005 hurricane season aggravated for the eastern bay by road construction on US 1.
2. The majority of regions assessed had chlorophyll-*a* and algal blooms rated as moderate (yellow).
3. The majority of regions assessed where the chlorophyll-*a* was higher than the median do not appear to be indicative of long-term negative trends.
4. The most commonly occurring condition was large spatial coverage of algal blooms and elevated chlorophyll-*a* concentrations.
5. Overall eutrophic symptom expressions were geographically variable and appear to be explainable from existing phenomenological conditions of hurricane activity overall exacerbated by road construction along US 1 in the eastern areas of the bay.
6. If water flows are improved to the southern estuaries we expect the water quality to improve and the number and scale of algal blooms to diminish. However, under current water flow conditions there will probably be little or no improvement in the conditions in the southern estuaries.
7. Monitoring of Barnes, Manatee and Blackwater Sounds was critical to being able to detect the impacts of road construction along US 1.
8. Monitoring long term consequences of nutrient releases into the southern estuaries from both natural (e.g. hurricanes) and human causes (e.g. road construction) and the interactions of hydrological restoration (e.g. more fresh water flow into the southern estuaries, particularly Florida Bay) is critical to continuing the evaluation and assessment restoration for the southern estuaries.

[a] Data in the Current Status column for the algal bloom indicator reflect data inclusive of calendar year 2006.

[b] The assumption being used for the 2-Year Prospects Column is: *There will be no changes in water management from the date of the current status assessment.*

**Fig. 4 – Example of the Stoplight Report Card System applied to Algal Blooms using CHLA as the indicator.**

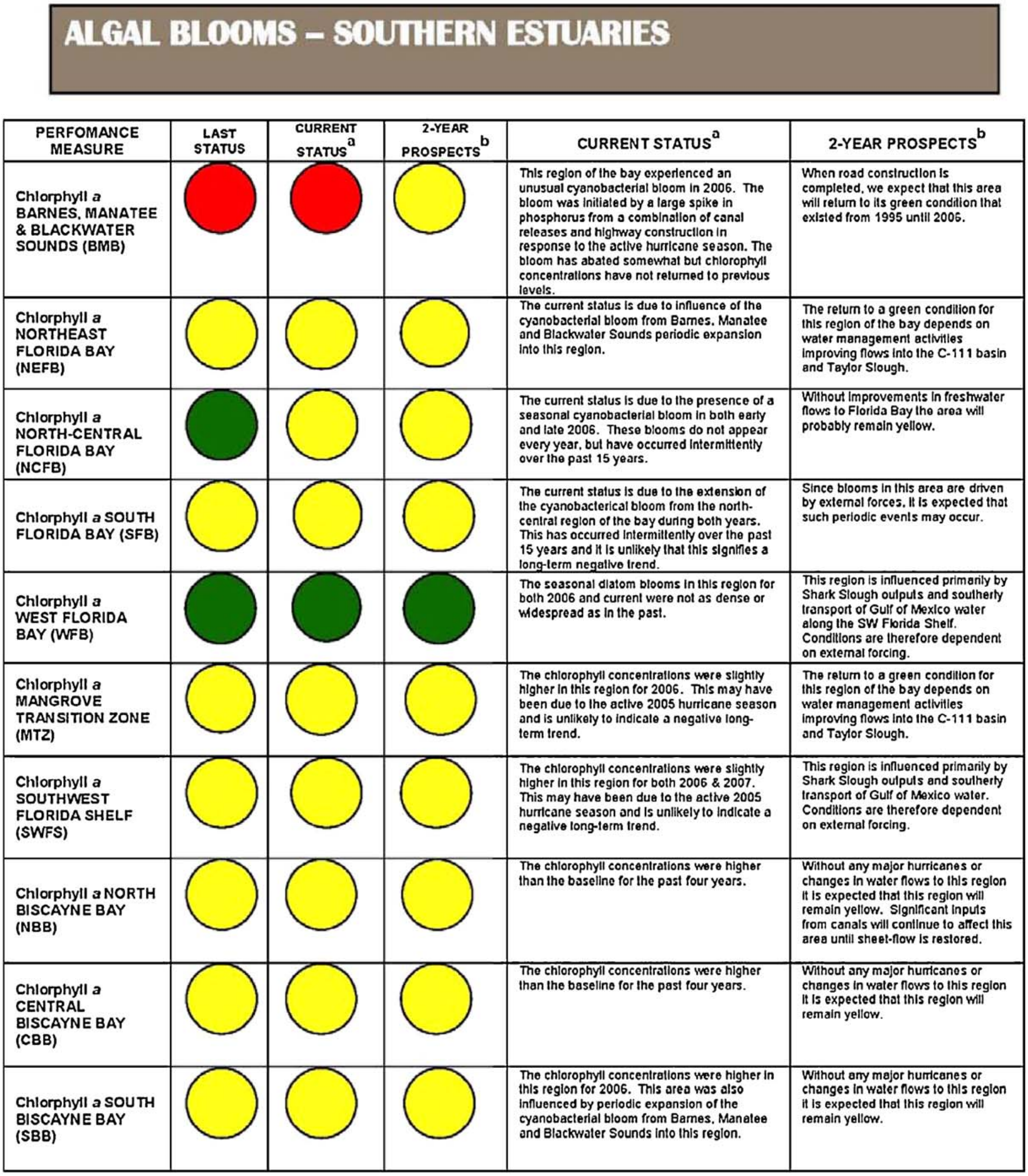
causing a great deal of physical disturbance, in anticipation of storm related flooding there was a large managed release of water that contained elevated levels of P prior to the first hurricane (Hurricane Katrina).

## 4. Discussion

### 4.1. *Communicating the phytoplankton bloom indicator*

As with the other Restoration Indicators, the phytoplankton bloom indicator may be expressed in Report Card format as one double-sided page (Fig. 4). The front page has the key findings for this indicator from the current assessment and provides recommendations to move or maintain the phytoplankton bloom indicator into the ‘‘green’’. The back page has the current, prior, and predicted future status for the phytoplankton bloom indicator in each of the ten sub-regions in conjunction with a brief summary explaining the ecological rationale for status assignment in each sub-region.

For 2006, the current criteria proved capable of detecting change from the reference condition and, in particular, highlighted deviations that were at least in part due to anthropogenic activities. The only sub-region that displayed a red status was BMB and this is because of a phytoplankton bloom that likely was initiated by several factors, including



ALGAL BLOOMS – SOUTHERN ESTUARIES

| PERFOMANCE MEASURE | LAST STATUS | CURRENT STATUS[a] | 2-YEAR PROSPECTS[b] | CURRENT STATUS[a] | 2-YEAR PROSPECTS[b] |
|---|---|---|---|---|---|
| Chlorophyll *a* BARNES, MANATEE & BLACKWATER SOUNDS (BMB) | 🔴 | 🔴 | 🟡 | This region of the bay experienced an unusual cyanobacterial bloom in 2006. The bloom was initiated by a large spike in phosphorus from a combination of canal releases and highway construction in response to the active hurricane season. The bloom has abated somewhat but chlorophyll concentrations have not returned to previous levels. | When road construction is completed, we expect that this area will return to its green condition that existed from 1995 until 2006. |
| Chlorophyll *a* NORTHEAST FLORIDA BAY (NEFB) | 🟡 | 🟡 | 🟡 | The current status is due to influence of the cyanobacterial bloom from Barnes, Manatee and Blackwater Sounds periodic expansion into this region. | The return to a green condition for this region of the bay depends on water management activities improving flows into the C-111 basin and Taylor Slough. |
| Chlorophyll *a* NORTH-CENTRAL FLORIDA BAY (NCFB) | 🟢 | 🟡 | 🟡 | The current status is due to the presence of a seasonal cyanobacterial bloom in both early and late 2006. These blooms do not appear every year, but have occurred intermittently over the past 15 years. | Without improvements in freshwater flows to Florida Bay the area will probably remain yellow. |
| Chlorophyll *a* SOUTH FLORIDA BAY (SFB) | 🟡 | 🟡 | 🟡 | The current status is due to the extension of the cyanobacterical bloom from the north-central region of the bay during both years. This has occurred intermittently over the past 15 years and it is unlikely that this signifies a long-term negative trend. | Since blooms in this area are driven by external forces, it is expected that such periodic events may occur. |
| Chlorophyll *a* WEST FLORIDA BAY (WFB) | 🟢 | 🟢 | 🟢 | The seasonal diatom blooms in this region for both 2006 and current were not as dense or widespread as in the past. | This region is influenced primarily by Shark Slough outputs and southerly transport of Gulf of Mexico water along the SW Florida Shelf. Conditions are therefore dependent on external forcing. |
| Chlorophyll *a* MANGROVE TRANSITION ZONE (MTZ) | 🟡 | 🟡 | 🟡 | The chlorophyll concentrations were slightly higher in this region for 2006. This may have been due to the active 2005 hurricane season and is unlikely to indicate a negative long-term trend. | The return to a green condition for this region of the bay depends on water management activities improving flows into the C-111 basin and Taylor Slough. |
| Chlorophyll *a* SOUTHWEST FLORIDA SHELF (SWFS) | 🟡 | 🟡 | 🟡 | The chlorophyll concentrations were slightly higher in this region for both 2006 & 2007. This may have been due to the active 2005 hurricane season and is unlikely to indicate a negative long-term trend. | This region is influenced primarily by Shark Slough outputs and southerly transport of Gulf of Mexico water. Conditions are therefore dependent on external forcing. |
| Chlorophyll *a* NORTH BISCAYNE BAY (NBB) | 🟡 | 🟡 | 🟡 | The chlorophyll concentrations were higher than the baseline for the past four years. | Without any major hurricanes or changes in water flows to this region it is expected that this region will remain yellow. Significant inputs from canals will continue to affect this area until sheet-flow is restored. |
| Chlorophyll *a* CENTRAL BISCAYNE BAY (CBB) | 🟡 | 🟡 | 🟡 | The chlorophyll concentrations were higher than the baseline for the past four years. | Without any major hurricanes or changes in water flows to this region it is expected that this region will remain yellow. |
| Chlorophyll *a* SOUTH BISCAYNE BAY (SBB) | 🟡 | 🟡 | 🟡 | The chlorophyll concentrations were higher in this region for 2006. This area was also influenced by periodic expansion of the cyanobacterial bloom from Barnes, Manatee and Blackwater Sounds into this region. | Without any major hurricanes or changes in water flows to this region it is expected that this region will remain yellow. |

**Fig. 4. (Continued).**

hurricane disturbance with associated canal discharges, road construction, and interactions of these factors. It is likely that without these anthropogenic actions (managed water release and road construction) this bloom would not have been as severe or prolonged. The 8 sub-regions that received a yellow rating likely had elevated CHLA in 2006 as a result of the active hurricane season at the end of 2005. Hurricanes often increase nutrient concentrations and thus CHLA through increased sediment re-suspension as a result of winds and increased runoff-associated nutrient loading as a result of rainfall. None of these 8 regions with elevated CHLA values was given a false red status, because their values remained within the bound of what had been typical of the pre-CERP condition.

### 4.2. *Goals and performance measures are established in the MAP for the indicator and the following metrics are being monitored*

Monthly water quality monitoring, including measurement of CHLA, as well as phytoplankton bloom performance measures, as described here, are included in the MAP. RECOVER conceptual ecological models identify 3 stressors influencing phytoplankton blooms in the southern estuaries, specifically Biscayne and Florida Bay. These are watershed development, water management, and hurricanes. The effect of two of these, watershed development and water management, fall to a significant degree under the auspices of CERP. As such, CERP activities and management decisions have the potential to significantly affect phytoplankton blooms in the southern estuaries.

Not surprisingly phytoplankton blooms are included in both the interim goals and performance measures for CERP. The interim goals include minimizing the frequency, duration, and intensity of phytoplankton blooms in Florida Bay. The performance measure related to this indicator is more general referring to overall water quality and identifying key components including nitrogen and phosphorous, phytoplankton blooms, dissolved oxygen, water color, turbidity, sedimentation rates, and toxins. However, as was discussed in the introduction, CHLA is a good indicator of overall water quality which integrates these key components. Although the target for phytoplankton blooms proposed in the performance measure is more restrictive than proposed herein (to minimize the magnitude, spatial extent, and frequency of phytoplankton blooms); the acceptable range of CHLA proposed in the performance measures was not nearly as restrictive. This is because the performance measure chlorophyll *a* thresholds were based on expert opinion; whereas, the indicator thresholds proposed herein are based on statistical analysis and better suited to detect quantitatively significant change in phytoplankton blooms.

Current water quality monitoring programs in this domain are maintained by FIU/SERC and NOAA/AOML as part of the MAP. These projects are complementary and maintain standard monitoring stations throughout all ten sub-regions of the southern estuaries which measure CHLA and other relevant water quality parameters (nutrients, turbidity, choromophoric dissolved organic matter (CDOM), dissolved oxygen, productivity, and respiration) (Fig. 1). This program also includes underway synoptic sampling to collect high spatial resolution CHLA data throughout much of the southern estuaries and monitors the adjacent ecosystem to investigate the potential impact on downstream ecosystems. This suite of monitoring is essential to assess the status of the CHLA indicator with respect to the interim goals and performance measures and determine the underlying cause for deviations from the reference condition. However, neither program is funded directly by MAP and both projects are vulnerable to cessation or reduction due to agency funding shortfalls. The feasibility of the CHLA indicator depends upon the continuation of these long-term monitoring programs.

### 4.3. *Longer-term science needs*

In addition to continued monitoring, further research and model development is needed is needed in order to understand cause and effect relationships and build reliable predictive capabilities. In particular, the fate and effects of dissolved organic nitrogen inputs from the Everglades and the effects of changing salinity on internal nutrient cycling (especially in sediments) needs to be assessed. Quantitative evaluations of multiple factors that will change with restoration and that may influence bloom dynamics also need to be made via model analysis (particularly with a water quality model). Such evaluations include not only the effects of changing nutrient inputs, but also the effects of changing salinity, water residence time, seagrass community cover and productivity, sediment stability, and growth of grazers.

The ability to predict phytoplankton bloom response to CERP is dependent upon the further refinement of the Environmental Fluid Dynamics Code Model that has been developed as a task of CERP's FBFKFS. This model is designed to predict the intensity, duration, and spatial distribution of phytoplankton blooms in Florida Bay and the nearshore SW Florida Shelf as CERP is implemented. A similar model is required for Biscayne Bay. However, further model development and refinement is needed to accurately predict CHLA in the southern estuaries. Given such refinement the model could be calibrated against the pre-CERP environment, the baseline condition discussed herein. With such a quantitative tool, we will be able to directly evaluate how CERP projects have altered phytoplankton bloom behavior in this region.

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## REFERENCES

Boyer, J.N., Briceño, H.O., 2006. FY2005 Annual Report of the South Florida Coastal Water Quality Monitoring Network. SFWMD/SERC Cooperative Agreement #C-15397. SERC Tech. Rep. # T-326. http://serc.fiu.edu/wqmnetwork/Report%20Archive/2005CWQMN.pdf.

Boyer, J.N., Keller, B., 2007. Nutrient dynamics. In: Hunt, J.H., Nuttle, W. (Eds.), Florida Bay Science Program: A Synthesis of Research on Florida Bay. Fish and Wildlife Research Institute Technical Report TR-11, pp. 55–76.

Boyer, J.N., Fourqurean, J.W., Jones, R.D., 1997. Spatial characterization of water quality in Florida Bay and Whitewater Bay by multivariate analysis: zones of similar influence (ZSI). Estuaries 20, 743–758.

Boyer, J.N., Fourqurean, J.W., Jones, R.D., 1999. Seasonal and long-term trends in water quality of Florida Bay (1989–1997). Estuaries 22, 417–430.

Brand, L., 2002. The transport of terrestrial nutrients to South Florida coastal waters. In: Porter, J.W., Porter, K. (Eds.), The Everglades, Florida Bay and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook. CRC Press, pp. 361–414.

Butler, M.J., Hunt, J.H., Herrnkind, W.F., Childress, M.J., Bertelsen, R., Sharp, W., Matthews, T., Field, J.M., Marshall, H.G., 1995. Cascading disturbances in Florida bay, USA: cyanobacteria blooms, sponge mortality, and implications for juvenile spiny lobsters *Panulirus argus*. Marine Ecology-Progress Series 129, 119–125.

Caccia, V.G., Boyer, J.N., 2005. Spatial patterning of water quality in Biscayne Bay Florida as a function of land use and water management. Marine Pollution Bulletin 50, 1416–1429.

CERP RECOVER Monitoring and Assessment Plan, 2004. http://www.evergladesplan.org, http://www.evergladesplan.org/pm/recover/recover_docs/mgmt_plan/rec_aam_pmp_final_aug_2004.pdf.

Childers, D.L., Boyer, J.N., Davis, S.E., Madden, C.J., Rudnick, D.T., Sklar, F.H., 2006. Nutrient concentration patterns in the oligotrophic ''upside-down'' estuaries of the Florida Everglades. Limnology and Oceanography 51, 602–616.

Committee on Restoration of the Greater Everglades Ecosystem (CROGEE), 2002. Florida Bay Research Programs and Their Relation to the Comprehensive Everglades Restoration Plan. National Academies Press, 54 p.

Cullen, J.J., 1982. The deep chlorophyll maximum Comparing vertical profiles of chlorophyll a. Canadian Journal of Fisheries and Aquatic Science 39, 791–803.

Environmental Protection Agency (EPA), 2001. Nutrient Criteria Technical Guidance Manual: Estuarine and Coastal Marine Waters. National Service Center for Environmental Publications (NSCEP).

Florida Bay Program Management Committee, 2004. The Strategic Science Plan for Florida Bay. In: Nuttle, W. (Ed.), Florida Bay Program Management Committee (http://www.aoml.noaa.gov/flbay), 48 p.

Fourqurean, J.W., Robblee, M.B., 1999. Florida Bay: a history of recent ecological changes. Estuaries 22, 345–357.

Fourqurean, J.W., Jones, R.D., Zieman, J.C., 1993. Processes influencing water column nutrient characteristics and phosphorus limitation of phytoplankton biomass in Florida Bay, USA: inferences from spatial distributions. Estuarine, Coastal Shelf Science 36, 295–314.

Hakanson, L., Bryhn, A.C., Blenckner, T., 2007. Operational effect variables and functional ecosystem classifications—a review on empirical models for aquatic systems along a salinity gradient. International Review of Hydrobiology 92, 326–357.

Hitchcock, G.E. Phlips, E.J., Brand, L., Morrison, D., 2007. Plankton Blooms. In: Hunt, J.H., Nuttle, W. (Eds.), Florida Bay Science Program: A Synthesis of Research on Florida Bay. Fish and Wildlife Research Institute Technical Report TR-11, pp. 77–91.

Hu, C., Muller-Karger, F.E., Lee, Z.-P., Carder, K.L., Roberts, B., Walsh, J.J., Weisberg, R.H., He, R., Johns, E., Lee, T., Kuring, N., Patch, J., Ivey, J., Coble, P.G., Heil, C., Vargo, G.A., Zepp, R.G., Steidinger, K., McRae, G., Boyer, J., Jones, R., Kirkpatrick, G., Mueller, E., Pierce, R., Culter, J., Keller, B., Hunt, J., 2002. Satellite images track ''black water'' event off Florida coast. EOS 83, 281–285.

Jurado, J.L., Hitchcock, G.L., Ortner, P.B., 2007. Seasonal variability in nutrient and phytoplankton distributions on the southwest Florida inner shelf. Bulletin of Marine Science 80, 21–43.

Kelble, C.R., Johns, E.R., Nuttle, W.K., Lee, T.N., Smith, R.H., Ortner, P.B., 2007. Salinity patterns of Florida Bay. Estuarine Coastal and Shelf Science 71, 318–334.

Kelble, C.R., Ortner, P.B., Hitchcock, G.L., Boyer, J.N., 2005. Attenuation of photosynthetically available radiation (PAR) in Florida Bay: potential for light limitation of primary producers. Estuaries 28, 560–571.

Lee, T.N., Johns, E., Melo, N., Smith, R.H., Ortner, P.B., Smith, D., 2006. On Florida Bay hypersalinity and water exchange. Bulletin of Marine Science 79, 301–327.

Lee, T.N., Melo, N., Johns, E., Kelble, C., Smith, R., Ortner, P., 2008. On water renewal and salinity variability in the northeast subregion of Florida Bay. Bulletin of Marine Science 82, 83–105.

Madden, C.J., McDonald, A.A., Cunniff, K., Rudnick, D., Fourqurean J., 2009. Development of ecological indicators for assessing seagrass status and trends in Florida Bay. Ecological Indicators (this issue).

Millie, D.F., Weckman, G.R., Paerl, H.W., Pinckney, J.L., Bendis, B.J., Pigg, R.J., Fahnenstiel, G.L., 2006. Neural net modeling of estuarine indicators: hindcasting phytoplankton biomass and net ecosystem production in the Neuse (North Carolina) and Trout (Florida) Rivers USA. Ecological Indicators 6, 589–608.

Nuttle, W.K., Fourqurean, J.W., Cosby, B.J., Zieman, J.C., Robblee, M.B., 2000. The influence of net freshwater supply on salinity in Florida Bay. Water Resources Research 36.

Peterson, B.J., Chester, C.M., Jochem, F.J., Fourqurean, F.W., 2006. Potential role of sponge communities in controlling phytoplankton blooms in Florida Bay. Marine Ecology-Progress Series 328, 93–103.

Phlips, E.J., Badylak, S., 1996. Spatial variability in phytoplankton standing crop and composition in a shallow inner-shelf lagoon, Florida Bay, Florida. Bulletin of Marine Science 58, 203–216.

Rudnick, D.T., Madden, C., Kelly, S., Bennett, R., Cunniff, K., 2006. Report on Algae Blooms in Eastern Florida Bay and Southern Biscayne Bay. South Florida Water Management District Report.

Rudnick, D.T., Ortner, P.B., Browder, J.A., Davis, S.M., 2005. A conceptual ecological model of Florida Bay. Wetlands 25, 870–883.

Rudnick, D.T., Chen, Z., Childers, D., Boyer, J.N., Fontaine, T., 1999. Phosphorus and nitrogen inputs to Florida Bay: the importance of the Everglades watershed. Estuaries 99, 398–416.

Steele, J.H., 1962. Environmental control of photosynthesis in the sea. Limnology and Oceanography 7, 137–150.

Tomas, C.R., Bendis, B., Johns, K., 1999. Role of nutrients in regulating plankton blooms in Florida Bay. In: Kumpf, H., Steidenger, K., Sherman, K. (Eds.), The Gulf of Mexico Large Marine Ecosystem: Assessment, Sustainability, and Management. Blackwell Science, Malden, MA, pp. 323–327.

Yarbro, L.A., Carlson Jr., P.R., 2008. Community oxygen and nutrient fluxes in seagrass beds of Florida Bay, USA. Estuaries and Coasts 31, 877–897.

Zhang, J.Z., Fischer, C.J., Ortner, P.B., 2004. Potential availability of sedimentary phosphorus to sediment resuspension in Florida Bay. Global Biogeochemical Cycles 18.

Zieman, J.C., Fourqurean, J.W., Frankovich, T.A., 1999. Seagrass die-off in Florida Bay (USA): long-term trends in abundance and growth of *Thalassia testudinum* and the role of hypersalinity and temperature. Estuaries 22, 460–470.