available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ecolind

Submerged aquatic vegetation and bulrush in Lake Okeechobee as indicators of greater Everglades ecosystem restoration

Matthew C. Harwell[a,*], *Bruce Sharfstein*[b]

[a] *A.R.M. Loxahatchee National Wildlife Refuge, U.S. Fish and Wildlife Service, 10218 Lee Rd., Boynton Beach, FL 33473, USA*

[b] *South Florida Water Management District, P.O. Box 24680, West Palm Beach, FL 33416, USA*

ARTICLE INFO

Article history:
Received 2 April 2008
Received in revised form
20 November 2008
Accepted 23 November 2008

Keywords:
Ecosystem indicators
Giant bulrush
Habitat integrator
Lake Okeechobee
SAV
Scirpus californicus
South Florida

ABSTRACT

Lake Okeechobee, Florida, located in the middle of the larger Kissimmee River-Lake Okeechobee-Everglades ecosystem in South Florida, serves a variety of ecosystem and water management functions including fish and wildlife habitat, flood control, water supply, and source water for environmental restoration. As a result, the ecological status of Lake Okeechobee plays a significant role in defining the overall success of the greater Everglades ecosystem restoration initiative. One of the major ecological indicators of Lake Okeechobee condition focuses on the near-shore and littoral zone regions as characterized by the distribution and abundance of submerged aquatic vegetation (SAV) and giant bulrush (*Scirpus californicus* (C.A. Mey.) Steud.). The objective of this study is to present a stoplight restoration report card communication system, common to all 11 indicators noted in this special journal issue, as a means to convey the status of SAV and bulrush in Lake Okeechobee. The report card could be used by managers, policy makers, scientists and the public to effectively evaluate and distill information about the ecological status in South Florida. Our assessment of the areal distribution of SAV in Lake Okeechobee is based on a combination of empirical SAV monitoring and output from a SAV habitat suitability model. Bulrush status in the lake is related to a suitability index linked to adult survival and seedling establishment metrics. Overall, presentation of these performance metrics in a stoplight format enables an evaluation of how the status of two major components of Lake Okeechobee relates to the South Florida restoration program, and how the status of the lake influences restoration efforts in South Florida.

1. Introduction and background

Lake Okeechobee is a 1800 km^2 freshwater lake located at the head of the Greater Everglades ecosystem in South Florida, USA (see Fig. 1 in Doren et al., 2009). Lake Okeechobee is very shallow (mean depth of approximately 3 m) relative to its size, and water column depths vary (minimum of 2.69 m NGVD in 2007; maximum of 5.72 m in 1947; NGVD = 1929 National Geodetic Vertical Datum) as a function of rainfall and as a result of multi-use management demands for flood control, agricultural and urban water supply (Aumen, 1995). The littoral zone and near-shore pelagic region provides valuable fish and wildlife habitat resources and is a potential keystone source of water for environmental restoration. Lake Okeechobee has been completely surrounded by the Herbert Hoover Dike since the 1960s and currently is made up of three distinct

* *Corresponding author*. Tel.: +772 562 3909x255.
E-mail address: matthew_harwell@fws.gov (M.C. Harwell).
1470-160X/$ – see front matter
doi:10.1016/j.ecolind.2008.11.009

regions (Fig. 1). The middle of the lake includes a 1200 km^2 highly eutrophied pelagic zone (3–5 m deep NGVD) where the foodweb is primarily dominated by planktonic producers. The littoral zone of the lake is comprised of a 400 km^2 mixed marsh community of submerged aquatic vegetation (SAV) and emergent vegetation, including spike rush (*Eleocharis cellulosa*). A 200 km^2 near-shore region (generally at depths shallower than 2 m) becomes hydrologically semi-uncoupled from the pelagic zone under low lake stages, and provides additional vegetative habitat for SAV and giant bulrush (*Scirpus californicus* (C.A. Mey.) Steud.) (Zhang et al., 2007). It is the littoral zone and near-shore region of the lake that is the focus of our indicator.

The emergent vegetation community in Lake Okeechobee provides nesting habitat and food resources for economically important sport fish populations, wading birds, migratory waterfowl, alligators, and the federally listed endangered Everglade snail kite *Rostrahamus socialabilus* (Havens and Gawlik, 2005). Lake Okeechobee's SAV community, occupying the near-shore region of the lake (defined here as the area lakeward of the emergent plant community out to a depth of approximately 2 m NGVD when present), provides habitat for fish and wildlife, a substrate for periphyton that can sequester nutrients from the water column, and stabilizes sediments (e.g., Vadeboncoeur and Steinman, 2002).

The conceptual ecological models that capture the littoral zone emergent and near-shore SAV mosaic of Lake Okeechobee have evolved over time (RECOVER, 2004, 2007b; Havens and Gawlik, 2005). Several major factors interact to influence the structure of the littoral zone emergent and SAV mosaic (Fig. 2) in Lake Okeechobee, including altered hydroperiod (Fig. 3), excessive phosphorus loading, water clarity, and the introduction and expansion of exotic plants (Havens et al., 1996, 2004; Steinman et al., 2002; Havens and Gawlik, 2005; Hanlon and Brady, 2005). As seen elsewhere in this special issue of *Ecological Indicators*, our indicator is anchored by several broadly defined hypotheses, modified from those initially developed for the Comprehensive Everglades Restoration Plan's (CERP) system-wide Monitoring and Assessment Plan (RECOVER, 2004), including:

In the near-shore and littoral zones, the distribution of native and exotic plants primarily is determined by hydroperiod and water depth.

Prolonged periods of deep water, combined with increased turbidity and physical damage from wind-driven waves, have dramatically reduced the spatial extent and biomass of near-shore bulrush stands and submerged aquatic vegetation.

Large scale perturbations such as hurricanes or prolonged droughts have major long-term, and unpredictable, impacts on both the emergent and submerged aquatic plant community.

As one vehicle for communicating progress regarding restoring the greater Everglades Ecosystem, the Science Coordination Group of the South Florida Ecosystem Restoration Task Force has adopted the use of a stoplight restoration report card (Doren, 2006) to present the status of a suite of ecological indicators described throughout this special issue of *Ecological Indicators*. The stoplight communication tool conveys information in a familiar, culturally associated format that is easily understood (Schiller et al., 2001; Doren et al., 2009). The inherent dynamic complexity of the South Florida system

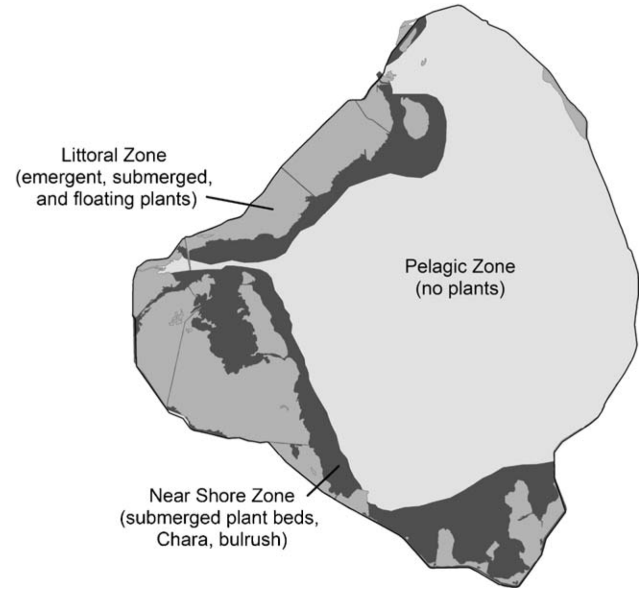

Fig. 1 – Map of Lake Okeechobee delineating the littoral zone and near-shore region.

translates into a recognition of the role of hysteresis in assessments of both environmental (e.g., Dong et al., 2002) and biological data (e.g., Trexler and Goss, 2009). The objective of this study is to present a stoplight communication tool for bulrush and SAV that incorporates a dynamic assessment component (sensu Trexler and Goss, 2009), and illustrates how it is intended to be used to describe the status of these important plant communities in the near-shore and littoral zones of Lake Okeechobee.

1.1. *Indicator history*

Emergent Vegetation—Bulrush: the first comprehensive map describing the distribution and areal coverage of littoral zone emergent vegetation was developed in the early 1970s (Pesnell and Brown, 1977), building upon earlier survey work (Sincock, 1957). A more detailed vegetation map was developed in 1996, and the most recent published map with detailed GIS layers was derived from 2003 color infrared aerial photography (see James and Zhang (2008) for the map and information on how the map was prepared). Historically, there were about 810 ha of bulrush on Lake Okeechobee (Pesnell and Brown, 1977), but in 2005, there were only 115 ha along the edge of the northwest marsh (James and Zhang, 2008).

Remote sensing data have been combined with field monitoring and targeted research to better understand the ecological dynamics of giant bulrush. Field measurements include regular stem counts in representative bulrush stands in Lake Okeechobee, and stem counts in beds with a history of damages due to herbicide treatment application for interspersed water hyacinth (*Eichornia crassipes* (Mart.) Solms.) (James and Zhang, 2008). Laboratory experiments have concentrated on the dynamics of bulrush seed germination as it relates to hydroperiod, and on the influence of hydroperiod to survival and vegetative propagation (C. Hanlon, pers. commun.).

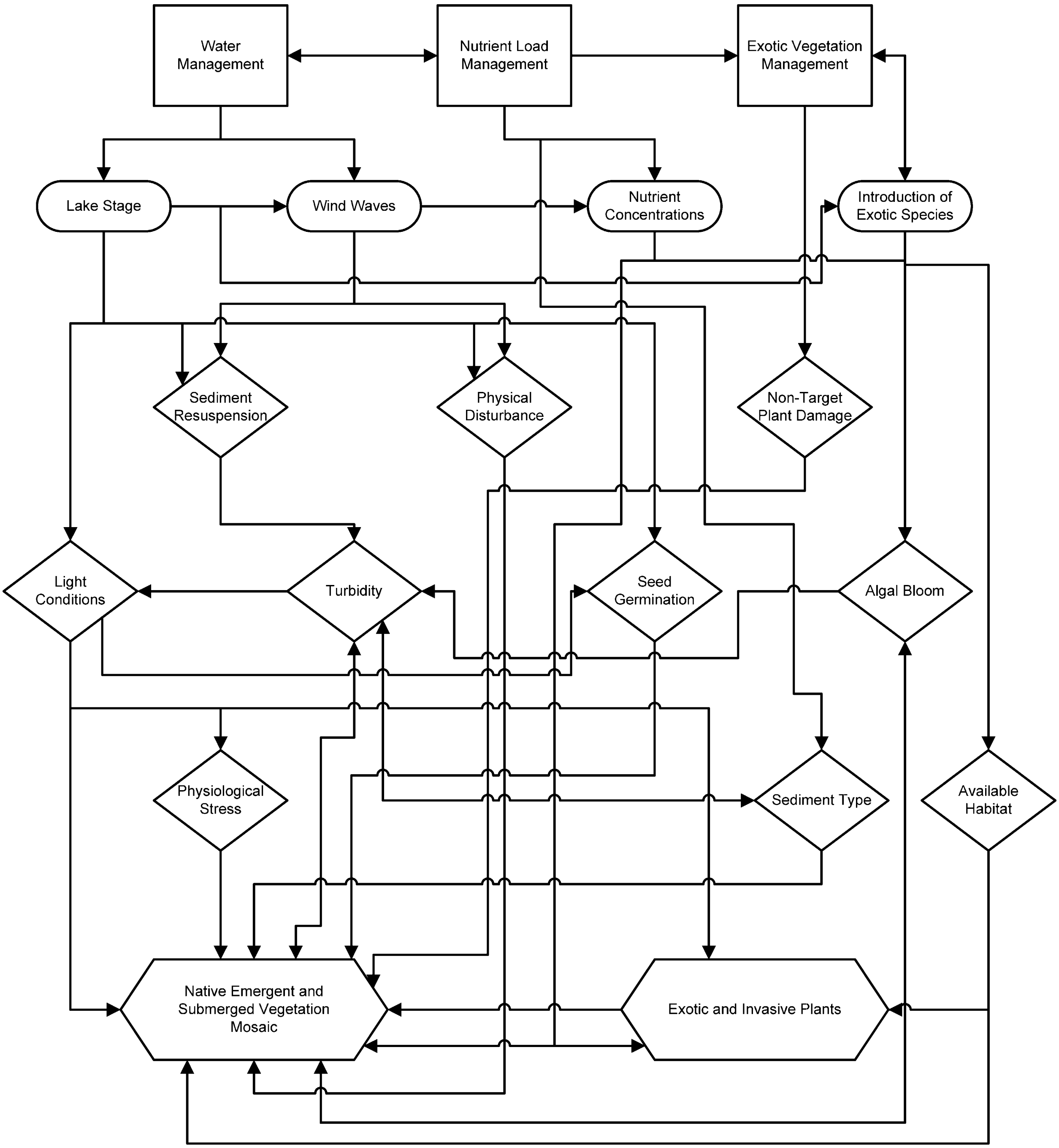

Fig. 2 – Conceptual ecological model of littoral zone emergent vegetation and near-shore region SAV in Lake Okeechobee.

The distribution of bulrush along the northwest marsh edge of Lake Okeechobee has been closely monitored since 1999 through vegetation mapping of three geographically separate areas of the lake using color infrared aerial orthophotographs. Bulrush along the lakeward edge of the emergent marsh is mapped annually, the western marsh is mapped every 2 years, and the remaining marsh is mapped no less than once every 5 years. Bulrush distribution along the entire western marsh or portions of the marsh has been documented nearly every year since 1999 (James and Zhang, 2008). Bulrush coverage varied from 68 to 116 ha (Table 1). The increase in bulrush coverage between 1999 and 2001 occurred in conjunction with a large reduction in lake stage during a managed draw down in 2000 (Steinman et al., 2002) and prolonged drought from 2000 to 2001, although no bulrush areal coverage data were available for 2000. A subsequent reduction in bulrush coverage occurred after 2001 as a result of continued prolonged exposure of sediments for more than 4 months, followed by relatively rapid re-flooding that resulted in water depths exceeding 2 m.

SAV—historical SAV biomass and distribution data exist from transect studies conducted in the late 1980s and early 1990s when Zimba et al. (1995) estimated that about 16,187 ha of SAV existed. Since 1999, SAV monitoring has occurred

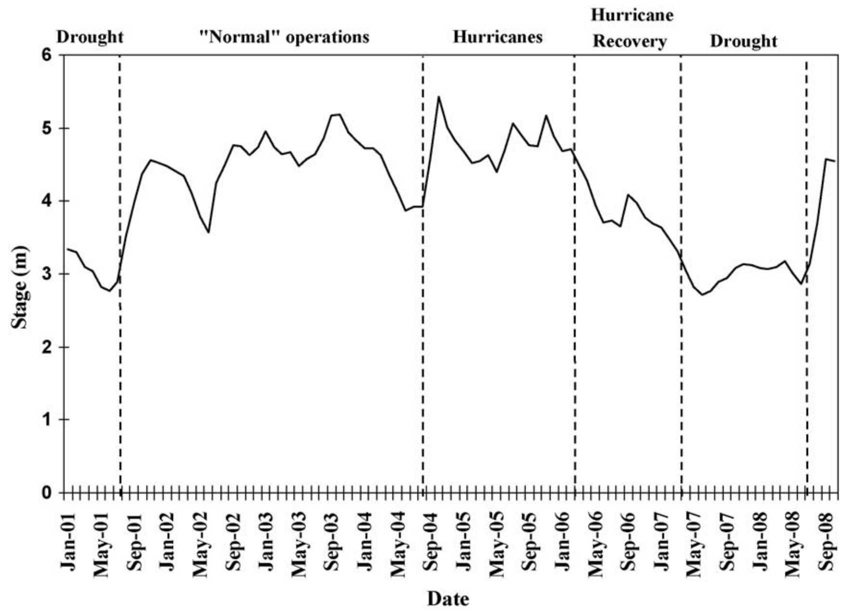

Fig. 3 – Stage hydrograph for Lake Okeechobee from 2001 to 2008 (in 1929 NGVD). Periods of different environmental conditions (e.g., drought, "normal" operations, hurricanes) are indicated with vertical dashed lines.

Table 1 – Areal coverage of bulrush (*Scirpus californicus*) in the near-shore region of Lake Okeechobee. Data from James and Zhang (2008).

Year	Hectares
1999	78
2001	108
2002	78
2003	68
2005	116

regularly in Lake Okeechobee, encompassing a wide range of hydrological and environmental conditions. Dominant SAV species found in Lake Okeechobee include *Hydrilla verticillata* (L.F.) Royle, *Vallisneria americana* Michx., *Najas guadalupensis* (Spreng) Morong, *Ceratophyllum demersum* L., *Utricularia* spp., and *Potamogeton illinoensis* Morong. *Chara* spp. is the dominant macroalgae in Lake Okeechobee (Grimshaw et al., 2005).

SAV annual mapping is performed near the end of the peak growing season (every August–September). Details about this program are available at Havens et al. (2002), and most recent mapping results presented in James and Zhang (2008). The entire near-shore of Lake Okeechobee is divided into square grids of 1000 m × 1000 m, resulting in approximately 750 sampling sites. Water depth, Secchi disc depth (a measure of water transparency), sediment type, presence versus absence of SAV by taxa, and a qualitative estimate of overall plant biomass (sparse, moderate and dense) are recorded for each site. Maps are then developed with spatial extent of each SAV species calculated in acres. This sampling regime documents the total acreage and type of plants that the lake gained (or lost) under the prevailing hydrologic conditions of a given growth cycle year. SAV coverage in Lake Okeechobee varies over time with the highest recorded coverage of SAV in Lake Okeechobee occurring in 2004 at nearly 22,258 ha. However, the areal extent of the SAV community is quite dynamic, as evidenced by the lake supporting less than 1214 ha in 2006 (Zhang et al., 2007; James and Zhang, 2008). By 2007, areal coverage of SAV had recovered to approximately 11,331 ha; however, unlike the past few years, the community was dominated by the macroalgae *Chara* spp. (98% of total SAV in 2007), with vascular aquatic species accounting for less than 202 ha.

1.2. *Significance of the indicator to greater Everglades ecosystem restoration*

Ecological indicators of emergent vegetation and SAV in the near-shore and littoral zones of Lake Okeechobee are integrative in their characterization of habitats that serve multiple ecological functions in an overall complex food web. These functions include periphyton, primary consumers such as macroinvertebrates, fish, wading birds, and other avifauna. Additionally, bulrush and SAV represent sensitive and germane indicators of ecological status of this region of the lake. Both SAV and bulrush can be related to combinations of environmental stressors, including lake stage and water column turbidity, which are the primary factors that affect water clarity and light penetration. The emergent vegetative community, like SAV, is very dynamic, with relatively short response times to changes in water depth, physical disturbance (e.g., tropical weather systems; Havens et al., 2001), and management activities to control exotic and invasive species. As restoration projects and other complementary efforts improve hydrological and water quality conditions within the lake, significant SAV and bulrush areal coverage expansion and increased biomass are expected. As a result of data collected during the past 9 years, the probability for successful trend detection with this assessment tool is moderate to high.

2. Communicating the Lake Okeechobee indicators

2.1. Indicator metrics

The restoration goal for littoral zone emergent vegetation and near-shore region SAV is primarily focused on spatial extent. Additionally, the ratio of vascular to non-vascular plants is also an important metric for SAV as much of the SAV community is comprised of pioneer species, such as *Chara* spp., following periods of unsuitable environmental conditions for SAV (e.g., high water, drought); those species do not provide optimal habitat or water quality benefits (RECOVER, 2007a). Spatial coverage targets are evaluated by comparison to anecdotal or empirically measured best conditions from the recent past (e.g., Havens et al., 2002). That is, restoration targets are pragmatically based on best observed ecological conditions which have been documented in the littoral zone and near-shore region of a highly managed and physically altered lake ecosystem, not on pre-drainage or pre-dike conditions.

Bulrush—as there is no consistent measurement of overall areal coverage of bulrush, targets for emergent vegetation in the littoral zone of Lake Okeechobee are challenging to enumerate given the limited information available on the emergent vegetation community as a whole (Doren, 2006). The restoration goal for spatial extent of bulrush identifies the desire for a more continuous and thicker band of bulrush located along the western edge of the lake (length of approximately 50 km) given the highly managed nature in the lake. Although the current CERP performance measure for bulrush (RECOVER, 2007a) does not define an explicit ultimate target, it is probable that the maximum areal coverage of bulrush, as reported by Pesnell and Brown (1977), could be re-established given successful restoration of the lake's quality of water and a sustained ability to appropriately manage lake stage. Given these information challenges, bulrush suitability presently is best characterized by hydrology for development of an indicator metric for assessing Lake Okeechobee-wide condition of bulrush (sensu Doren, 2006).

SAV—when conditions are favorable in the littoral zone and near-shore region of the lake, SAV can occupy more than 16,187 ha in Lake Okeechobee, but coverage can be reduced to near zero when conditions are poor (e.g., Havens et al., 2004). Ideally, the target for SAV is to have an average annual coverage at the end of each growing season of 16,187 ha or more, where at least half this acreage is comprised of vascular species. While this metric presently focuses on areal coverage, the addition of a temporal component also would be beneficial (see Section 3 below).

2.2. The stoplight restoration report card system applied to Lake Okeechobee

Bulrush—the influence of water depth on the persistence of giant bulrush was studied to examine how to minimize impacts of stage level manipulation on long-term bulrush survival. Currently, experiments are being conducted to identify the specific effects of various hydroperiod regimes and water transparencies on growth, vegetation propagation and seed bank germination (James and Zhang, 2008). These data will help refine our understanding of bulrush growth dynamics as they relate to lake stage and water quality, the two parameters most likely to be affected by Lake Okeechobee restoration efforts. Recent evidence also suggests that the physical effects of tussocks of free floating aquatic vegetation (e.g., *E. crassipes* (water hyacinth) and *Pistia stratiotes* L. (water lettuce)) exerting wind and wave-driven pressure against bulrush stands, as well as non-targeted spray damage from treating such vegetation in bulrush stands, may have substantial and long-lasting effects on the bulrush in Lake Okeechobee (James and Zhang, 2008). Nevertheless, our current understanding is that undisturbed bulrush persists when water depths are below of 0.9 m (lake stage of 3.9–4.1 m NGVD), but prolonged periods of high-water inundation (e.g., water depths above 4.3–4.6 m depending on duration), or extended periods of dry conditions (lake stage less than 3.0 m NGVD and duration greater than 4 months) may cause bulrush stands to decrease in areal coverage, especially since bulrush is more susceptible to disturbances such as herbivory or strong winds (Zhang et al., 2007). A suitability index (see below) was developed to relate hydrological condition to bulrush status based on this information.

SAV—the ability to satisfy a spatial coverage target for SAV is determined by inter-dependent environmental stressors (e.g., lake stage and water transparency which combine to determine light availability in the water column). Thus an assessment of the status of SAV in Lake Okeechobee needs to be interpreted in the context of how much SAV exists in the lake relative to model projections of suitable SAV habitat.

A model has been developed that predicts potential SAV habitat availability for a given year, based on multiple years of monitoring data. SAV habitat availability is evaluated as a function of water transparency, which is indirectly measured by total suspended solids, and lake water levels (Zhang et al., 2007). Using bathymetry information, this model is applied to the SAV spatial sampling grid with GIS, and predicts areas within the near-shore region of Lake Okeechobee that are suitable SAV colonization habitats when favorable water depth, light penetration, and turbidity conditions occur.

Combining metrics—further refinement of the SAV habitat suitability model (see Section 3 below) and results from the ongoing bulrush research described above will be valuable for refinement of the individual SAV and bulrush indicators. Future efforts will focus on development of a combined index as many factors which affect the status of bulrush and SAV are the same. Environmental conditions such as light availability may have dominant effects on both bulrush and SAV. For example, lower stages result in higher light availability which may be favorable for both plant indicators (albeit the phenology of the emergent bulrush may be different than SAV). Additionally, water depth is a common environmental factor for the two indicators, although ideal water depths for these two metrics may not be the same, and additional work is needed to explore these relationships. Preliminary results from recent bulrush studies suggest that bulrush expansion may be enhanced by lake stages sufficiently low enough that inshore water levels in the near-shore region become too shallow to support vascular SAV habitat (i.e., the extent of available habitat for SAV colonization in the inshore portion of

Table 2 – Scoring habitat suitability for bulrush (*Scirpus californicus*) in Lake Okeechobee for a given year.

Lake stage (m NGVD)	Effect	Condition	Color
5.0 or >	Serious damage any exposure period	Poor	Red
4.9	Serious damage for >1 month	Poor	Red
4.6	Serious damage for >3 months	Poor	Red
4.3	Damage if exposed for >6 months	Poor	Red
4	Survives and grows slowly	Acceptable	Yellow
3.7	Grows well	Optimal	Green
3.4	Grows well	Optimal	Green
3	Grows well and recruits via seed germination after 6–10 weeks	Optimal	Green
<3.0	Serious Damage though desiccation after 1 month	Red	Red

the near-shore region is reduced; e.g., Havens et al., 2004). The relationship between Lake Okeechobee stage and exposure of the littoral and near-shore zone is presented at: http://my.sfwmd.gov/gisapps/losac/sfwmd.asp, and described in Chang (2006).

2.3. *Components of the Lake Okeechobee stoplight restoration report card*

Bulrush—stage conditions in the Lake Okeechobee near-shore zone are applied for the bulrush indicator (Table 2).

SAV—three components are involved in the SAV indicator: (1) the annual areal distribution of SAV in the near-shore region of Lake Okeechobee; (2) the environmental conditions (water depth, transparency) recorded during the annual SAV mapping effort; (3) the SAV suitability model.

2.4. *Scoring and thresholds for the Lake Okeechobee stoplight restoration report card*

Bulrush—the first step for scoring the bulrush indicator involves application of a suitability index for bulrush in the littoral zone of Lake Okeechobee, based on monitoring and research information (Doren, 2006; Zhang et al., 2007) that helps to delineate between poor, acceptable, and optimal conditions for suitable bulrush establishment and survival as a function of lake stage for the present year (Table 2). The second step involves examining the suitability score for the present year along with suitability scored from the two prior years—a single-year snapshot of the status of bulrush is insufficient to characterize the spatio-temporal status of bulrush in Lake Okeechobee. Three consecutive years of performance scores (a time period identified based on our best professional judgment) are then assembled in sequence which is then compared to an interpretative matrix (Table 3) to derive an overall prediction of bulrush suitability. While the 3 years combine to influence the overall conclusion, the current year's status is afforded a slightly larger influence over that of other years as the following year is more strongly influenced by the current year than prior years. For example, a 3-year sequence green → yellow → red results in a composite score of red, while a sequence of red → yellow → green results in a composite score of green.

The lake stages identified in Table 2 have different temporal components to them, with poor (red) conditions marked by either high or low lake stages having durations associated with those stages. At intermediate lake stages, conditions are relatively more favorable for bulrush, and at present, no durations are associated at those elevations. As a result, the hydrological surrogate used for bulrush does have limitations, including the inability to differentiate whether an extended period of steady lake stages is more or less optimal than an equivalent period with lake stages fluctuating within the bounds of the current management target of achieving maximum stage at the end of the wet season, and minimum stage at the end of the dry season.

SAV—the first step for scoring the status of SAV in Lake Okeechobee involves calculating the acreage of total SAV, and the percentage of total SAV acreage comprised of *Chara* spp. following Havens et al. (2002) and Zhang et al. (2007). Table 4A presents the scoring matrix for this component. The second step involves examining the Lake Okeechobee SAV suitability model performance for a given year determined by comparison of actual total SAV acres with modeled total SAV suitable habitat acres, expressed as a percentage of modeled SAV suitable habitat acres. Table 4B presents the scoring matrix for this component. The utility of the SAV suitability model focuses on applying SAV targets under environmental conditions that yield moderate SAV acreage.

The final assessment step combines the scoring results from the actual SAV acreage information and SAV modeling of suitable habitat components. Table 5 depicts the interpretation matrix that presents all potential combinations of the two SAV component scores and derives an overall inference. When actual SAV acreage has attained the coverage goal for a given year (as designated by green in Table 4A), the SAV acreage component drives the overall score of the final conclusion for that year (Table 4B). In essence, when SAV conditions are good and consistently attain the ultimate restoration coverage targets, results from the SAV habitat model results are not incorporated into the annual overall score—in effect, they are discounted. Likewise, when the actual SAV acreage is poor (red in Table 4A), the SAV acreage component drives the overall score of the final conclusion for that year (Table 4B). Only, when actual SAV acreage is moderate (yellow in Table 4A), does the habitat suitability aspect of the SAV modeling performance (from Table 4B) influence the overall score. When a moderate actual SAV acreage (yellow) is below that predicted by the SAV suitability model (green), the overall score is poor (red), suggesting that the SAV community is in worse than expected shape. When a moderate actual SAV acreage (yellow) is better than predicted by the SAV suitability model (red), the overall score is good (green), suggesting that SAV community is in better shape than expected. These latter scenarios attempt to capture

Table 3 – Interpretation matrix for assessing bulrush (*Scirpus californicus*) suitability in Lake Okeechobee based on past 3 years of status. The status for each year is independently determined using the performance scoring approach in Table 1; 3 years of performance scores (2 years ago; 1 year ago; present year) are then put together in sequence (columns). The sequence is compared to this interpretation matrix which presents all potential combinations (rows) in order to derive an overall conclusion (far right column). For example, a hypothetical 3-year sequence of yellow, red, green yields in an overall conclusion of yellow.

2 yrs ago	Last year	This year	Conclusion
G	G	G	G
G	G	Y	Y
G	G	R	Y
G	Y	G	G
G	Y	Y	Y
G	Y	R	R
G	R	G	Y
G	R	Y	Y
G	R	R	R
Y	G	G	G
Y	G	Y	Y
Y	G	R	R
Y	Y	G	G
Y	Y	Y	Y
Y	Y	R	R
Y	R	G	Y
Y	R	Y	R
Y	R	R	R
R	G	G	G
R	G	Y	Y
R	G	R	Y
R	Y	G	G
R	Y	Y	Y
R	Y	R	R
R	R	G	Y
R	R	Y	R
R	R	R	R

hysteresis effects resulting from the dynamical nature of the system (sensu Trexler and Goss, 2009). Thus, in addition to the simple presentation of the indicator, limited information about the environmental condition of Lake Okeechobee for a given year is important to provide a consistent understanding of the interpretation of this assessment. The reporting vehicle for the indicators presented in this special issue (described in Doren et al., 2009) allows for this contextual information to be presented (e.g., Doren et al., 2008).

This metric has been applied to several years of SAV data (Fig. 4). Overall SAV status in 2002 would be considered to be green (green in acreage and green in model performance); SAV in 2003 yellow (yellow and yellow, respectively); SAV in 2004 and 2005 green (yellow and green, respectively).

Table 4A – Overall score for SAV acreage in Lake Okeechobee is based on a total SAV acreage component and a percent of total SAV acres comprised of *Chara*.

Total SAV ha*	*Chara*[a]	Overall score
≥16,187	≤50%	Green
≥16,187	>50%	Yellow
<16,187	≤50%	Yellow
<16,187	>50%	Red

[a] % of total SAV acres.

Table 4B – The score for Lake Okeechobee SAV model performance for a given year is determined by comparison of actual total SAV acres with modeled total SAV suitable habitat acres, expressed as a percentage of modeled SAV suitable habitat acres.

Model performance[a]	Score
>75%	Green
25–75%	Yellow
<25%	Red

[a] % of total SAV acres.

3. Discussion

3.1. *Effectiveness of the Lake Okeechobee indicator for ecological restoration*

The use of a stoplight format report card to characterize the ecological condition of Lake Okeechobee has specific and limited applications. These indicators describe the condition of the near-shore region of the lake, but not the status of the entire lake. Although there likely are links between the ecological condition of the near-shore, littoral and pelagic zones, caution is warranted in applying this metric to assessing the ecological status of the entire lake.

In general, conditions in Lake Okeechobee fluctuate widely as a result of disturbance cycles of very wet and dry water

Table 5 – Interpretation matrix for assessing overall SAV condition in Lake Okeechobee. The status for SAV acreage component is determined using the performance scoring approach in Table 4A; the modeling component scoring is derived from the approach in Table 4B. For a given year, the scores for each component are compared to this interpretation matrix which presents all potential combinations in order to derive an overall conclusion (far right column). See narrative in text for interpretations.

Acreage component	Model component	Conclusion
Green	Green	Green
Green	Yellow	Green
Green	Red	Green
Yellow	Green	Red
Yellow	Yellow	Yellow
Yellow	Red	Green
Red	Green	Red
Red	Yellow	Red
Red	Red	Red

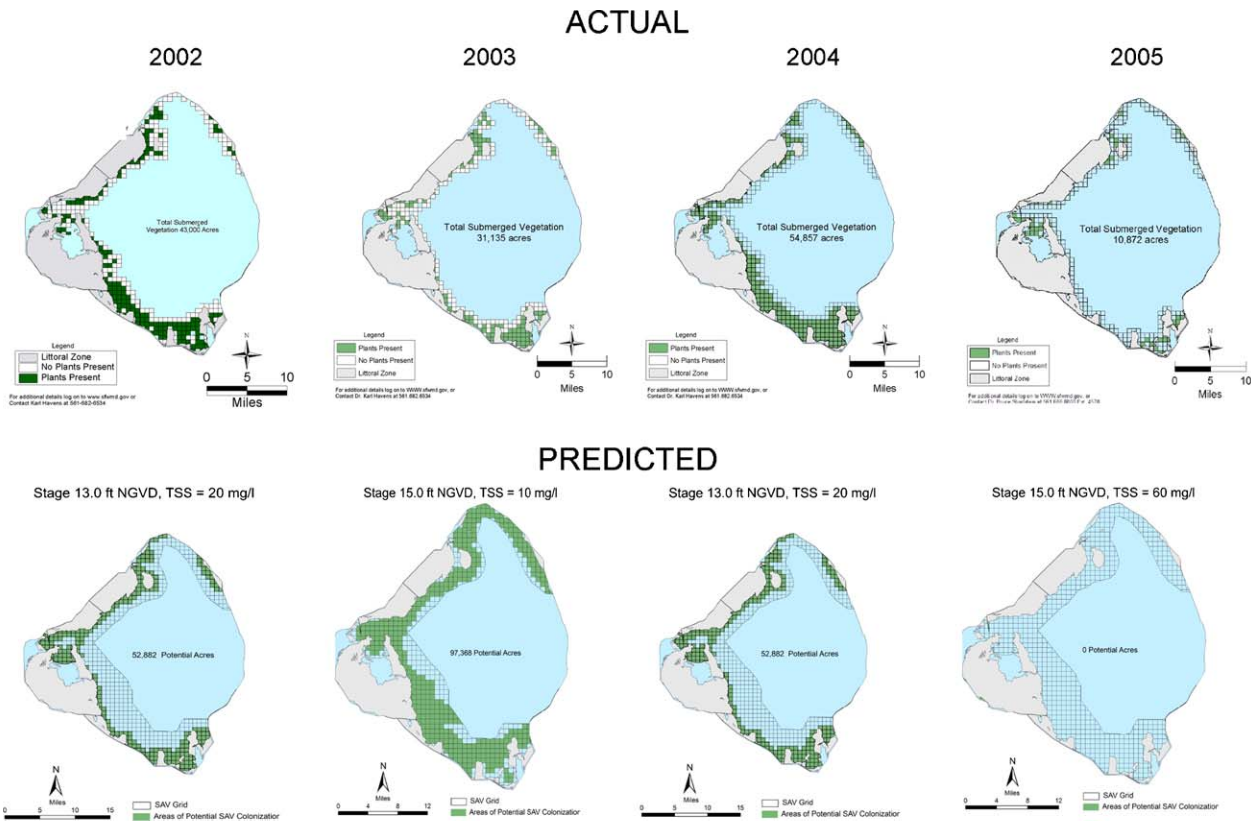

Fig. 4 – Actual spatial distribution on SAV in Lake Okeechobee (top) versus model predicted distribution of SAV (bottom) from 2002 to 2005.

years and the nearby passage of tropical weather systems. Management decisions as they relate to flood control and water supply needs, and potential ecological impacts to downstream receiving waters, also are influenced by these climatic fluctuations and disturbance events. As a result, any indicator that presents short-term trends in lake condition (e.g., bulrush and SAV presented here) needs to be interpreted in the larger context of long-term environmental conditions and long-term restoration efforts. For example, if a hurricane passes over Lake Okeechobee and eliminates SAV and lingering high turbidity reduces light availability (e.g., Havens et al., 2001) one might expect a red light for a status indicator even if water levels after the storm remained suitable for SAV. If water clarity improves several years later and non-vascular SAV (e.g., Charophytes) re-appear, one might expect a yellow light for improvement in overall SAV. Finally, if viable propagation stocks remain intact, vascular SAV species may re-establish and attain sufficient areal coverage such that the indicator becomes green. Unusually wet years, recurring tropical storms, sustained drought years, or some other as yet unanticipated event or combination thereof could reset this condition and return this indicator to red. As a result, use of a simplified indicator based on the existing SAV performance measure as a stand-alone metric of Lake Okeechobee condition may not be adequate. Accordingly, the indicator should be employed judiciously as a metric upon which to base management decisions affecting the lake or status of the longer-term restoration effort. This limitation may not be a result of the stoplight format per se, but reflects the way in which the current metric is parameterized. Inclusion of a multi-year component in the indicator (e.g., a rolling-average of year-to-year SAV acreage) might help to improve the utility of this indicator. Similarly, including components that characterize lake stage, turbidity, and seed bank viability might help with the ability to interpret areal SAV coverage results.

3.2. *Communicating the Lake Okeechobee indicator*

The stoplight restoration report card is intended to function as a communication tool based on, but not limited to, existing performance measures for ecological attributes identified as part of the CERP/RECOVER Monitoring and Assessment Plan. There is a wealth of information on how to best communicate science to a diverse audience, including the general public (e.g., Schiller et al., 2001). The guidelines and obstacles to scientific communication of this indicator – and the others in this special issue of *Ecological Indicators* – are discussed in depth by Doren et al. (2009). By applying experimental, monitoring, and modeling information to develop suitability indices for emergent vegetation and SAV in the near-shore region of Lake Okeechobee, the indicator communication tools are suitable for application to several existing ecosystem assessments of the lake (e.g., Doren, 2006; RECOVER, 2007b; Zhang et al., 2007; James and Zhang, 2008).

Lake Okeechobee littoral zone emergent and near-shore SAV communities respond along a range of temporal scales from nearly instantaneous (e.g., hurricane disturbance; Havens et al., 2001) to seasonally, annually and multi-year. Short-term responses tend to occur as a result of major perturbations or as a function of natural cycles of growth and senescence whereas longer cycles tend to occur as a result of cumulative or synergistic effects. Therefore, one limitation of indexes, such as those presented here involves the need to also consider additional information about related parameters and recent trends.

The reporting of this indicator (e.g., Doren et al., 2008) provides the reader with more than just a red, yellow, or green symbol; the reporting vehicle also provides additional information to put the indicator in a larger context (e.g., whether the results of the indicator was influenced by natural processes or variability or by anthropogenic actions). Further, the reporting format points the reader to where to find additional information to allow the reader to make an informed interpretation of this communication tool as called for by Harwell et al. (1999).

3.3. *Longer-term science needs*

One way to develop long-term science is to focus on the information needed to provide greater in-depth assessment of an indicator. For bulrush, the longer-term science need involves continued delineation of distribution and abundance of vegetation by remote sensing (Richardson and Harris, 1995) as well as developing a clearer understanding of the relationships between plant condition and propagation strategies as they relate to water depth and duration. The present inability of the bulrush index to differentiate whether a period of steady, optimal lake stages (for bulrush) is more or less ideal than a period of variable lake stages within that optimal range of stages needs further attention. Additional efforts to understand the status of the emergent vegetation community in the littoral zone of Lake Okeechobee include the need to assess changes in other favorable emergent species (e.g., spikerush, beakrush, willow and pond apple). An example of a narrative discussion on changes in some of these plants is presented in Zhang et al. (2007). An understanding of the effects of invasive natives (e.g., *Typha domingensis* Pers. (cattail)) and invasive exotics such as *Panicum repens* L. (torpedograss) would also aid in refining emergent vegetation metrics.

A second-order refinement of the SAV indicator should include information from studying the spatial distribution of SAV by species type and the competitive relationships between species that lead to transitions between monotypic and multi-specific beds (including multi-tier density classification) among and across years; an understanding of individual species light requirements (Grimshaw et al., 2002, 2005) and reproductive physiology; and improved knowledge of the behavior of the seed (vascular plants) and oospore (*Chara* spp.) bank and sexual and vegetation propagation. Additional incorporation of higher-temporal resolution SAV transect mapping (in place since 1999) might also help in better understanding changes in SAV as a function of environmental conditions in this highly managed lake. This monitoring program examines SAV at up to 78 sites located along 16 transects, with a varying sampling frequency ranging from quarterly to monthly (depending on anticipated dynamic changes in the plant population) (Zhang et al., 2007). As discussed in Section 3.1, continued refinement of the SAV suitability model to incorporate new higher resolution bathymetry, and to optimize the spatial and temporal component of the light climate related input data and increases the range of environmental conditions observed (e.g., extremely low lake stages of 2008) would increase the rigor of the indicator. Ultimately, the scoring and thresholds of the SAV indicator in Lake Okeechobee should be refined as our knowledge base expands.

Acknowledgements

We would like to thank Andy Rodusky, Greg Graves, and Larry Gerry for constructive review and input on earlier versions of this manuscript, and Andy Rodusky and Chuck Hanlon for technical input. We would like to thank Jenn Stiner for assistance with Fig. 1 and Amy Peters for assistance with Fig. 2. This manuscript benefited greatly from input by several journal reviewers. We acknowledge the South Florida Ecosystem Restoration Task Force and Science Coordination Group – in particular the efforts of Greg May and Rock Salt – in making the publication of the special issue of *Ecological Indicators* possible. We also thank G. Ronnie Best, U.S. Geological Survey for additional financial support in the publication of this special issue. The opinions expressed herein do not necessarily represent the opinions of the U.S. Fish and Wildlife Service or the South Florida Water Management District.

References

Aumen, N.G., 1995. The history of human impacts, lake management, and limnological research on Lake Okeechobee, Florida (USA). Archiv. Hydrobiol. Spec. Issues Advanc. Limnol. 45, 1–16.

Chang, F., 2006. South Florida Water Management District the Lake Okeechobee Stage-Area-Capacity Lookup Application. URISA J. (online) 1, 18.

Dong, Q., McCormick, P.V., Sklar, F.H., DeAngelis, D.L., 2002. Structural instability, multiple stabe states, and hysteresis in periphyton driven by phosphorus enrichment in the Everglades. Theoret. Popul. Biol. 61, 1–13.

Doren, R.F. (Ed.), 2006. Indicators for Restoration: South Florida Ecosystem Restoration. Report to the South Florida Ecosystem Restoration Task Force.

Doren, R.F., Trexler, J.C., Harwell, M., Best, G.R., Editors, 2008. System-wide Indicators for Everglades Restoration 2008 Assessment. Unpublished Technical Report. 39 pp. Available at: http://www.sfrestore.org.

Doren, R.F., Trexler, J.C., Gottlieb, A.D., Harwell, M.C., 2009. Ecological indicators for system-wide assessment of the greater Everglades ecosystem Restoration Program. Ecol. Indic. 9, S2–S16.

Grimshaw, H.J., Havens, K., Sharfstein, B., Steinman, A., Anson, D., East, T., Rodusky, A., Jin, K.R., 2002. The effects of shading on morphometric and meristic characteristics of Wild Celery, *Vallisneria americana* transplants from Lake Okeechobee Florida. Archiv. Hydrobiol. 155, 65–81.

Grimshaw, H.J., Sharfstein, B., East, T., 2005. The effects of shading on *Chara zeylanica* Klein ex Wild. and associated epiphytes. Archiv. Hydrobiol. 162, 253–266.

Hanlon, C.G., Brady, M., 2005. Mapping the distribution of torpedograss and evaluating the effectiveness of torpedograss management activities in Lake Okeechobee, Florida. J. Aquat. Plant Manage. 43, 24–29.

Harwell, M.A., Myers, V., Young, T., Bartuska, A., Gassman, N., Gentile, J.H., Harwell, C.C., Appelbaum, S., Barko, J., Causey, B., Johnson, C., McLean, A., Smola, R., Templet, P., Tosini, S., 1999. A framework for an ecosystem integrity report card. Bioscience 49, 543–556.

Havens, K.E., Gawlik, D.E., 2005. Lake Okeechobee conceptual ecosystem model. Wetlands 25, 908–925.

Havens, K.E., Aumen, N.G., James, R.T., Smith, V.H., 1996. Rapid ecological changes in a large subtropical lake undergoing cultural eutrophication. Ambio 25, 150–155.

Havens, K.E., Harwell, M.C., Brady, M.A., Sharfstein, B., East, T.L., Rodusky, A.J., Anson, D., Maki, R.P., 2002. Large-scale mapping and predictive modeling of submerged aquatic vegetation in a shallow eutrophic lake. Sci. World J. (online) 2, 949–965.

Havens, K.E., Jin, K.R., Rodusky, A.J., Sharfstein, B., Brady, M.A., East, T.L., Iricanin, N., James, R.T., Harwell, M.C., Steinman, A.D., 2001. Hurricane effects on a shallow lake ecosystem and its response to a controlled manipulation of water level. Sci. World J. (online) 1, 44–70.

Havens, K.E., Sharfstein, B., Brady, M.A., East, T.L., Harwell, M.C., Maki, R.P., Rodusky, A.J., 2004. Recovery of submerged plants from high water stress in a large subtropical lake in Florida, USA. Aquat. Bot. 78, 67–82.

James, R.T., Zhang, J., 2008, Chapter 10: Lake Okeechobee Protection Program—State of the Lake and Watershed. (In G. Redfield (Ed.) 2008 South Florida Environmental Report. South Florida Water Management District, West Palm Beach, FL). Available at: http://www.sfwmd.gov.

Pesnell, G.L., Brown, R.T., 1977. The major plant communities of Lake Okeechobee and their associated inundation characteristics as determined by gradient analysis. Technical Publication 77-1, South Florida Water Management District, West Palm Beach, FL.

RECOVER, 2004. Monitoring and Assessment Plan. U.S. Army Corps of Engineers Jacksonville District, FL, and South Florida Water Management District, West Palm Beach, FL. Available at: http://www.sfwmd.gov.

RECOVER, 2007. Development and Application of Comprehensive Everglades Restoration Plan System-wide Performance Measures. U.S. Army Corps of Engineers Jacksonville District, FL, and South Florida Water Management District, West Palm Beach, FL. Available at: http://www.evergladesplan.org.

RECOVER, 2007. Final 2007 System Status Report. U.S. Army Corps of Engineers, Jacksonville District, FL, and South Florida Water Management District, West Palm Beach, FL. Available at: http://www.evergladesplan.org/.

Richardson, J.R., Harris, T.T., 1995. Vegetation mapping and change detection in the Lake Okeechobee marsh ecosystem. Archiv. Hydrobiol. Spec. Issues Advanc. Limnol. 45, 17–39.

Schiller, A., Hunsaker, C.T., Kane, M.A., Wolfe, A.K., Dale, V.H., Suter, G.W., Russell, C.S., Pion, G., Jensen, M.H., Konar, V.C., 2001. Communicating ecological indicators to decision makers and the public. Cons. Ecol. 5, 19.

Sincock, J.L. (1957) A study of the vegetation on the northwest shore of Lake Okeechobee. Appendix D in Wallace, H.E. and Counselman, C.J. Recommended Program for Northwest Shore of Lake Okeechobee. Florida Game and Fresh Water Fish Commission. pp. 176–227.

Steinman, A., Havens, K., Hornung, L., 2002. The managed recession of Lake Okeechobee, Florida: integrating science and natural resource management. Cons. Ecol. 6, 17.

Trexler, J.C., Goss, C.W., 2009. Aquatic fauna as indicators for Everglades restoration: applying dynamic targets in assessments. Ecol. Indic. 9, S108–S119.

Vadeboncoeur, Y., Steinman, A., 2002. Periphyton function in lake ecosystems. Sci. World J. 2, 1449–1468.

Zhang, J., James, R.T., Ritter, G., Sharfstein, B., 2007. Chapter 10: Lake Okeechobee Protection Program—State of the Lake and Watershed. In: G. Redfield (Ed.) 2007 South Florida Environmental Report. South Florida Water Management District, West Palm Beach, FL). Available at: http://www.sfwmd.gov.

Zimba, P.V., Hopson, M.S., Smith, J.P., Colle, D.E., Shireman, J.V., 1995. Chemical composition and distribution of submersed aquatic vegetation in Lake Okeechobee, Florida (1989–1991). Archiv. Hydrobiol. Spec. Issues Advanc. Limnol. 45, 233–240.