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Stress in mangrove forests: Early detection and preemptive rehabilitation are essential for future successful worldwide mangrove forest management



Roy R. Lewis III ^{a,*}, Eric C. Milbrandt ^b, Benjamin Brown ^c, Ken W. Krauss ^d, André S. Rovai ^e, James W. Beever III ^f, Laura L. Flynn ^a

^a Coastal Resources Group, Inc., 23797 NE 189th Street, Salt Springs, FL 32134, USA

^b Sanibel-Captiva Conservation Foundation, 900A Tarpon Bay Road, Sanibel, FL 33957, USA

^c Charles Darwin University, Research Institute for Environment and Livelihoods (RIEL), Red Building 1, Ellengowan Drive, Casuarina, Darwin, NT 0909, Australia

^d U.S. Geological Survey, Wetland and Aquatic Research Center, 700 Cajundome Blvd., Lafayette, LA 70506, USA

^e Universidade Federal de Santa Catarina, Departamento de Ecologia e Zoologia, Campus Universitário, Trindade, Florianópolis, SC 88080-900, Brazil

^f Southwest Florida Regional Planning Council, 1926 Victoria Avenue, Fort Myers, FL 33901, USA

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ABSTRACT

Mangrove forest rehabilitation should begin much sooner than at the point of catastrophic loss. We describe the need for "mangrove forest heart attack prevention", and how that might be accomplished in a general sense by embedding plot and remote sensing monitoring within coastal management plans. The major cause of mangrove stress at many sites globally is often linked to reduced tidal flows and exchanges. Blocked water flows can reduce flushing not only from the seaward side, but also result in higher salinity and reduced sediments when flows are blocked landward. Long-term degradation of function leads to acute mortality prompted by acute events, but created by a systematic propensity for long-term neglect of mangroves. Often, mangroves are lost within a few years; however, vulnerability is re-set decades earlier when seemingly innocuous hydrological modifications are made (e.g., road construction, blocked tidal channels), but which remain undetected without reasonable large-scale monitoring.

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1. Introduction

Mangrove forests are often stressed beyond their limits of survival for a number of reasons (e.g., hydrological change, artificial in-filling of sediments, subsidence, climatic variability). Much of the scientific literature discusses acute stress events, which are readily recognized, researched, and assigned cause. Yet for mangrove forests stress often manifests over decades with little apparent incremental change signalling their future demise. Indeed, individual stress events may have occurred decades before mortality is formally detected; the classic case involves road construction disrupting critical tidal flows (Jiménez et al., 1985; Botero and Salzwedel, 1999; Rivera-Monroy et al., 2006) or damming of rivers reducing sediment supplies to deltaic mangroves (Syvitski et al., 2005; Lovelock et al., 2015). Early detection of stress and preemptive rehabilitation have the potential to alleviate much of this loss, at least in areas having adaptive, or even reactive, management plans in place.

* Corresponding author. E-mail address: LESrrl3@aol.com (R.R. Lewis). It is not our intent to conduct an intensive review of the published literature on stress in mangrove forests, but rather to suggest what Swart et al. (2013) termed "...new transformative solutions" for responses to environmental stress, and apply that concept to preemptive management of mangrove mortality. Swart et al. emphasized climate stress testing and development of proposed solutions with "[a] focus on thresholds..." to "...foster a salient dialogue between decision makers and scientists about the magnitude of acceptable change, when unacceptable conditions could occur, how likely these conditions are and which adaptation pathways to consider." Stanturf et al. (2014) also referenced "transformative adaptations" to the challenge of forest restoration in general, noting adaptations "...may be responsive or anticipatory, reactive or proactive" and also termed "intervention ecology" after Hobbs et al. (2011).

Eslami-Andergol et al. (2015) in discussing "abrupt ecosystem regime shifts" in intertidal ecosystems note that "detecting an approaching tipping point may help management to adapt to or mitigate the effects of catastrophic change." We intend to propose a transformative approach to do just that through a recommended protocol for early detection and preemptive rehabilitation of mangrove forests before they degrade to nearly complete lack of cover (i.e. "deforestation" from Putz and Redford, 2010) and significantly reduce ecological function. We term this approach "mangrove forest heart attack prevention" in line with the major cause of mangrove stress being modified tidal water flows and exchange, much like blocked blood flows to a heart. The medical parallels are clear; long-term degradation of function leads to mortality prompted by acute events, but created by a systematic propensity for long-term neglect.

2. Brief summary of the mangrove forest stress literature

Lugo and Snedaker (1974) in the first modern review of the ecological structure and function of mangrove forests presented a simple model of the "...essential structural and functional attributes of mangrove ecosystems...", later modified by Lugo (1978) and Lugo et al. (1981) and reproduced here as Fig. 1 (from Lugo et al., 1981). Changes in a single individual stressor pathway (e.g., partial changes in hydroperiod; Fig. 1) may lead to eventual mortality of the entire mangrove ecosystem or of critical components (e.g., understory regeneration) for continued persistence. Managers need to be able to detect this gradual mortality and make adjustments while it is occurring. The model identifies five different types of stressors (Lugo, 1998), quoted as:

"(1) those that change the main energy source (i.e., tides, runoff, etc.), (2) those that divert a fraction of the inflow of resources to the mangroves before these resources can be used within the mangroves, (3) those that remove photosynthate before [it is] stored or used by plants, (4) those that remove soil nutrients or mass from the system, and (5) those that affect metabolism... In general, the severity of the stress decreases from type 1 to type 5 stressors." (p. 427).

Lugo (1998) further notes that "this model depicts rehabilitation actions that reverse the conditions of the five types of stressors. For example, removing limiting factors or toxins, seeding or adding resources, restoring growth conditions, or restoring hydrological conditions or topography" might serve to rehabilitate the mangrove forest.

In general, the cost and difficulty of rehabilitation increases from actions that reverse type 5 stressors to those that reverse type 1 stressors (Fig. 1). For example, "it is more difficult to rehabilitate mangrove habitats (hydrology, topography) than it is to replace plants or overcome a limiting factor.". We have some differences of opinion on this latter statement, but the general concept is applicable. The title of the Lugo (1998) paper is "Mangrove Forests: a Tough System to Invade but an Easy one to Rehabilitate." Here we agree, but note that the state of the mangrove forest after stress impacts, and the time period to rehabilitate conditions of former forest structure and function, can vary considerably and need to be examined carefully to determine where financial and human resources are best invested in any mangrove forest rehabilitation project. Unfortunately, the justification for the rehabilitation process in terms of costs-to-benefits is more clear when the ecosystem is denuded. We suggest there should be priorities for rehabilitation based upon the stressors at play and the probable time to true rehabilitation, after rehabilitation actions are instituted. Such consideration is not now a routine part of mangrove management planning and



Fig. 1. Chronic stressors (types labelled 1–5) in mangrove ecosystems [redrawn from Lugo (1978) and Lugo et al. (1981), but with original wording, lettering, and connections]. Original caption: "Diagram illustrating the point of attack of stressors on wetland ecosystems, modified from Lugo (1978). An example is given for each type of stressor [see text]. Symbols are described in H.T. Odum (1967). Circles represent external forces acting on the ecosystem. Tanks represent storages of matter. Arrow-shaped symbols are used to illustrate the interaction of two flows, in this case the stressor and an ecosystem component. Plants are represented by the symbol labelled 'production' and all consumers are represented by the symbol labelled 'respiration'. Flows of energy and matter are undirectional and represented by solid lines. Energy drains are shown wherever there are energy transformations in order to comply with the second law of thermodynamics" (p. 130, Lugo et al., 1981). From the original document, "ecosystem complexity" appears to relate to structural complexity, such as the distribution of trees, species, aerial roots, seedlings, leaves and buds, etc. that define a mangrove forest when relatively free of environmental stressors.

rehabilitation processes. If mangroves look healthy from a distance, they are often assumed to be fine without conducting important verification either on-site or through remote sensing.

3. A new transformative approach

We suggest that a new approach is needed to address the issue of delayed mangrove forest loss to anthropogenic activities, and complications from issues such as climate change stress. Globally, direct forest loss is estimated at approximately 1–2.1% per year (Duke et al., 2007; Valiela et al., 2001), or approximately 150,000 ha per year, with total historical losses estimated at 35% (Valiela et al., 2001). Other types of losses related to habitat degradation are equally important to add to these statistics.

While the global mapping of mangrove forests from satellite imagery is a powerful approach to synthesize changes in large areas over time (Giri et al., 2011), the scale of specific natural and anthropogenic disturbances, such as roads, are often smaller than the 900 m² (30 m × 30 m) minimum mapping unit utilizing LANDSAT. Use of IKONOS (panchromatic resolution 1 m, multispectral 4 m), or one of several other satellite platforms (EROS, QUICKBIRD), can overcome this limitation; however, problems arise with the availability of legacy images that allow comparisons of images of the same area over decades to detect changes with time as is provided by LANDSAT, but with lesser resolution. Thus, the current estimate of 137,760 km² of mangrove area (Giri et al., 2011) also inherently does not address the ecological condition of mangroves that were included in the mapping.

This is especially concerning in well-studied regions of Florida, USA that have large areas of mangroves (e.g. Charlotte Harbor) protected and owned for public benefit, but are increasingly in a degraded ecological state because of various disturbances (Milbrandt et al., 2006; Proffitt et al., 2006; Harris et al., 2010). Management intervention can only be taken if degradation is known ahead of time. Most if not all of the managed mangroves in Florida are currently considered in "poor and declining condition" (Florida Fish and Wildlife Conservation Commission [FWC], 2012a). However, the revised 2012 Marine Wildlife Legacy Initiative by FWC (FWC, 2012b) addresses only coral reef restoration as the State's highest priority, and no mention of mangrove management or restoration is made under high priorities. The priority conservation actions for mangroves, where mentioned, are listed as "improving detection of pathogens, parasites, and biotoxins in marine organisms and the ability to rehabilitate impacted animals" (emphasis added) and "providing training on appropriate mangrove trimming..." (FWC, 2012a). None of these proposed conservation actions are likely to have any real impact on the health of mangrove forests in Florida. These types of management plans are repeated in mangrove habitat worldwide.

Current approaches to mangrove forest management as previously mentioned have been reviewed (Ellison and Farnsworth, 1996; Kairo et al., 2001; Biswas et al., 2009; Ong and Gong, 2013; UNEP, 2014). The recommended activities to improve mangrove management largely consist of recommendations for more private land acquisition which includes mangroves, better legal protections for mangroves, and expanded mangrove rehabilitation projects. The two former approaches seem logical, but depend upon the rule of law in many countries like Indonesia, Thailand, Malaysia, and Brazil, where laws already exist but are either not enforced or have been undergoing historical downgrading, downsizing, and degazettement (Pagliosa et al., 2012; Rovai et al., 2012a; Mascia et al., 2014).

The third approach (i.e., rehabilitation, sensu Field, 1998) also seems logical, but several authors have noted the current high failure rates of these efforts (Lewis, 2005; Samson and Rollon, 2008; Lewis and Brown, 2014; Brown et al., 2014). Failure is often noted in spite of clear published guidance about preventing common errors, and repeated clear guidance towards successful rehabilitation efforts (Lewis, 2000; 2005; Primavera et al., 2011; Lewis and Brown, 2014) using such

approaches as Ecological Mangrove Rehabilitation (EMR) (Lewis and Brown, 2014) and Community Based EMR (Lewis et al., 2006; Brown et al., 2014). Most rehabilitation efforts we are aware of do not apply these proven methods, but instead typically aim to plant mangroves in areas not suitable for their establishment, or in lower intertidal flats including seagrass meadows, where even successful efforts replace a valuable and established marine community (Primavera et al., 2012). We clearly distinguish problems with successful rehabilitation from other efforts with greater success that involve "afforestation" or "creation" of new mangrove habitat on accreting mud deposits, as reported by Saenger and Siddiqui (1993) in Bangladesh, where large areas have been planted with some success as accreting mud deposits reach the ideal elevation to support both planted and naturally recruited mangrove seedlings. Thus, planting may be justified if the goal is to facilitate a more rapid succession on otherwise suitable sites, or if specific mangrove species are desired. However, these ideal scenarios for reforestation are rare based upon our collective worldwide field experiences.

In spite of these problems, these previously recommended actions need to be continued, expanded, and improved. We further recommend a fourth parallel approach: early or preemptive rehabilitative efforts in stressed mangroves prior to complete loss of plant structure and ecological function, which we term "mangrove heart attack prevention". While the protection of mangrove boundaries are the best way to prevent losses of mangrove wetlands at large scales, the gradual decrease and eventual loss of mangroves due to small scale disturbances are a major threat to mangroves globally. The approach outlined describes the types of ecological threats and degradation. By adding search images, degradation can be identified when compared with previously GIS mapped areas and stored as a categorical index within the known boundaries of existing mangroves.

4. Mangrove heart attack prevention

Fig. 2 details five different hypothesized mangrove forest degradation and rehabilitation scenarios and the hypothesized loss (oxidation or erosion) or gain (sequestration) of carbon (C) during the illustrated processes, including general time frames. Solid curved arrows with the notation "C" are meant to indicate normal reported rates of loss or gain. Straight arrows with numerals are meant to indicate approximate time frames for the transitions between stages. These proposed timeframes are supported by empirical observations of the time required for the return of major ecosystem structural, functional, and edaphic properties, with emphasis on the C stocks and pathways (McKee and Faulkner, 2000; Osland et al., 2012). The dashed lines in Fig. 2 are meant to indicate collapse of organic soils, which are a major concern because any loss in elevation makes mangroves more susceptible to submergence from sea-level rise (Krauss et al., 2014).

Scenario 1 illustrates the typical "acute disturbance and natural recovery" process indicative of hurricane, typhoon, or tsunami damage to mangroves. Mangrove damage from these stochastic weather events are the most documented scientifically. An otherwise healthy mangrove forest will begin to recover from these disturbances over short time periods (2–3 years), assuming there is no underlying, overwhelming peat collapse (Cahoon et al., 2003), but taking perhaps as long as 20–30 years for complete recovery if large scale damage has resulted (Lugo and Snedaker, 1974; Lugo, 1980; Shafer and Roberts, 2008; Osland et al., 2012; Salmo et al., 2013; 2014). Lugo et al. (1981) suggest that stressors 1, 2, 4, and 5 (Fig. 1) are active in these processes. C losses would be large initially with sediment collapses reported in some cases (Lang'at et al., 2014). C sequestration would begin as soon as the secondary succession processes are underway, but depending on the rates of sea level rise, may or may not be able to keep up with relative sea level rise.

In all of these scenarios, successful rehabilitation is assumed to represent an end-point with healthy mangrove forests responding within their natural capacity to response to sea-level rise. Mangrove forests in many locations undergo both surface elevation surplus and deficit

ACUTE DISTURBANCE AND NATURAL RECOVERY



Fig. 2. Alternative disturbance and recovery processes in mangrove forests. Preemptive rehabilitation at Scenario 5 can prevent complete deforestation and collapse of organic soils (dashed line).

naturally relative to sea-level rise (Krauss et al., 2014; Lovelock et al., 2015; Sasmito et al., 2016; and references there-in); the focus of rehabilitation is to remove the anthropogenic barriers to the recovery of the site's natural response. Thus, C loss and gain also depend on the successional state of the system. In a progradation regime, C gain follows from the expansion of the intertidal zone and of the system towards the sea. However, under transgressive regime (e.g. eustatic increase of sea level), the intertidal zone and the system would be compressed, both

Collapse of organic soils—Question mark indicates unknown due to the anthropogenic impact from the land, and naturally, due to the increase of topographic slope.

Scenario 2 illustrates the impact of chronic disturbance, such as road construction that disrupts normal hydrology and results in a type 1 chronic stress (Fig. 1). Without active rehabilitation, there is no natural recovery. This scenario can lead to eventual mortality of mangroves over decades (Cordona and Botero, 1998; Rivera-Monroy et al., 2006), with early detection becoming a challenge.

Scenario 3 illustrates the impact of a chronic disturbance with long term stress such as the impoundment of mangroves for mosquito control or conversion to aquaculture ponds, and again chronic type 1 stress. Various attempts at rehabilitation are often undertaken in these cases, such as planting of mangroves inside such impoundments (Primavera et al., 2011). This action almost always fails because the stress itself is not alleviated. Even if some of these plants survive, the chronic lack of regular tidal exchange will limit the long term ecological functions and structural recovery in mangroves, and the recovery of normal rates of C sequestration. Fig. 3 illustrates such a condition at the Rookery Bay National Estuarine Research Reserve (RBNERR) in Naples, Florida, USA that has persisted for over 20 years, eventually culminating in complete mangrove mortality in multiple areas.

Scenario 4 documents chronic disturbance from impoundment, but at stage 4C, the removal of the stress (particularly type 1) and the release of the normal secondary succession processes (Rovai et al., 2012b), allow for recovery and the return of normal C sequestration and storage rates and other ecological functions. Lewis et al. (1985), Brockmeyer et al. (1997), and Rey et al. (2012) describe such successful large scale efforts to do this successfully by reconnecting mosquito control impoundments to critical tidal flows in the Indian River Lagoon in Florida, USA. This process has been termed "strategic breaching" by Lewis et al. (2006). Under some circumstances, recovery might not take place if too much antecedent soil loss prevents successful rehabilitation (question mark at scenario 4D). This scenario is of particular interest in Southeast Asian countries with thousands of hectares of abandoned maricultural ponds (Brown et al., 2014). For example, in the Philippines, a 9-ha abandoned pond was breached naturally with mangroves making a full recovery in 3 years, compared to the 15-20 years that it can take when unassisted, if recovery occurs at all (Primavera et al., 2012). Of note from a modelling study, the continuous presence of salinity and inundation stressors in "planted" mangroves may also eventually lead to a population collapse in 50 years if normal tidal hydrology is not restored, this despite mangroves demonstrating good growth in the first 20 years (Salmo and Juanico, 2015). Thus,



Fig. 3. Twenty hectare mangrove die-off area within the Rookery Bay National Estuarine Research Reserve, Naples, Florida, USA brought on by the construction of a road decades earlier. Photo credit: Cynthia Sapp, 2011.

without continued maintenance of tidal hydrology, carbon stocks gained initially may also be drastically reduced.

Finally, scenario 5 illustrates the essential message of this paper; long-term slow degradation of mangrove forests create inalienability of forest resilience to withstand acute catastrophic events. Thus chronic partial disturbance and the presence of type 1 and 2 stressors (Fig. 1) start the process of long term degradation that can lead to conditions as illustrated in Scenario 2, but is interrupted by early detection while the forest is still at least partially structurally intact, and ecologically functioning at some lowered level (Fig. 4). Because of intense anthropogenically imposed stressors (intended or unintended) on mangrove wetlands worldwide, scenario 5 is all too common. C loss has begun, but only slowly. Intervention at stage 5B–5C can prevent large scale losses of vegetation structure and ecological function, and reverse C losses, resulting in relatively quick recovery to full function and structure, estimated to be within 15–25 years in total time (Lewis, 2005; Osland et al. 2012; Salmo et al., 2013).

This is in contrast to the hypothesized recovery time of 25–50 years in Scenarios 1 and 4, or no recovery at all as hypothesized in Scenarios 2 and 3 (Fig. 2). Given limited resources to devote to the previously recommended mangrove management tools of land acquisition, legal protection, and rehabilitation *after* severe degradation, we suggest that early rehabilitative efforts in stressed mangroves prior to complete loss of plant structure and ecological function, or "mangrove heart attack prevention" through preemptive rehabilitation be given higher priority in future mangrove management plans.

5. How do we detect and quantify degradation, and prevent deforestation?

Changes in forest structure, and to a lesser extent function, have been routinely detected with structural measurements, but have also included remote sensing techniques (Husch et al., 1982; Middleton and Souter, 2016). A site index relating tree height to age is commonly used, and "crown coverage" as a measure of relative density has been used to estimate timber volume from aerial photographs. Husch et al. (1982) noted that "fine dot grids and crown density scales allow rapid estimation on vertical photographs." Today such manual tasks are replaced with computer analyses, and crown or canopy percent cover can be measured and easily be calculated. The methods might closely follow Keim et al. (2013) in the classification of forested wetland degradation using ordination of



Fig. 4. Stressed mangroves at Rookery Bay National Estuarine Research Reserve, Naples, Florida, USA created through hydrological isolation leading to persistent ponding and little tidal connectivity over the past few decades. While this is still technically a mangrove forest structurally, dead trees and a broken canopy clearly identify the ongoing stress.

Photo credit: Robin R. Lewis, 2010.

multi-temporal reflectance data and establishment of "vigor classes" which rank forested wetlands as: stressed, degrading, healthy, etc. While the most appropriate remote sensing techniques might depend a bit on the type of stress being targeted, large scale serial monitoring using acquired imagery from forested wetlands is now quite feasible (Middleton and Souter, 2016). Hiring qualified staff with training in this type of monitoring using remote sensing techniques by natural resource agencies has even become routine, although this specific task still requires ground truthing and training.

The work of Pool et al. (1977) and Cintrón et al. (1978) is supportive of these classifications and shows that the structure of a mangrove forest is closely correlated with stress in the forest. Important forest structure attributes to characterize mangrove health are biomass, basal area, canopy height, frequency, density, dominance, importance value and the resulting calculated Complexity Index (CI). The CI is determined from data gathered in fixed study plots, or using the point-centeredquarter method (Cintrón and Novelli, 1984), with simple formulation:

$CI = \frac{(of species of mangroves)(of stems)(basal area)(maximum height of mangroves)}{100}$

Cintrón and Novelli (1984) describe in detail the recommended methods of gathering and analyzing these types of data. Structural attributes typically are measured in restoration of impact (experimental) areas and reference (control) areas, and then compared over time. The calculated CI values can be applied to both sets of plant data for comparison purposes to define if a forest is under stress or, after detection and intervention, is being successfully rehabilitated. Eventual comparisons of control and treatment plots among themselves and with published data are necessary to enable any rational estimate of what changes in CI might occur with mangrove rehabilitation. In addition to collecting data and computing the relative CI, these data are subjected to statistical analysis and might be used as a means of establishing the health of a mangrove forest. Pool et al. (1977) note "a research effort was initiated to select the most meaningful ecosystem parameters for rapid, quantitative characteristics of numerous different mangrove systems... during time-limited study periods... several of these ecosystem variants have potential comparative value particularly in the development of testable hypotheses... [A]nother long-term objective... is to distinguish between natural variations in mangrove structure and function, and variations resulting from man-induced perturbations" (emphasis added). It is this latter focus that is similar to our proposed approaches for managers.

Cintrón et al. (1978) performed detailed field studies along the arid coastlines of Puerto Rico and reported:

"cyclic mortality and expansion of mangrove forests in response to cyclic events appears to be a common feature of arid coastlines... and care should be taken before attributing this mortality to other factors including man and isopods" (p. 120).

The latter reference apparently derived from the report of potential large-scale losses of mangroves in Florida due to an introduced species of boring isopod (Rehm and Humm, 1973), which Simberloff et al. (1978) attempted to refute, citing potential benefits of what turned out to be a native species.

The importance of separating natural variation from anthropogenic stress and degradation is emphasized by the introduction of the term "cryptic ecological degradation" (Dahdouh-Guebas et al., 2005a), which is defined as "qualitative ecological and socioeconomic degradation...and...changes in the areas suitable as mangrove habitat..." without obvious detection. The main findings of their study in Sri Lanka indicated that "...increase of freshwater flow...has led to a quantitative increase in mangrove forest areas, which is masking a disastrous qualitative shift from typical vulnerable mangrove species to

eurytopic mangrove associates and minor mangrove vegetation elements" (Dahdouh-Guebas et al., 2005a).

They further note "... the global need for monitoring and early warning of degradation for coastal ecosystems such as mangroves...". They cite Dahdouh-Guebas et al. (2005b) in recommending "...use of very high resolution remote sensing"...to... "provide much useful information on disappearance of or changes to typical species assemblages (species shifts, introgression by mangrove associates) at an early stage". We note that our challenge is to detect those changes at an early stage in the structure of a mangrove forest that might be indicative of reversible mangrove degradation (Salmo and Juanico, 2015). The imagery used by Dahdouh-Guebas et al. (2005b) was IKONOS (panchromatic resolution 1 m, multispectral 4 m), but several other satellite platforms are available (EROS, QUICKBIRD). Problems arise with the availability of legacy images that allow comparisons of images of the same area over decades to detect changes with time as is provided by LANDSAT, but with lesser resolution (30 m). Proposed remote sensing and field verification data analyses, as detailed in an example for a southwest Florida mangrove stress mapping study, is shown in Fig. 5 (Chandra Giri, unpublished).

6. A case study and viewpoint conclusions

Experimental approaches to early detection of mangrove forest degradation, and the reversal of that stress prior to deforestation, should be undertaken on a much larger scale than previously done. We further propose a combination of ground-truthing, quantitative forest structural sampling, quantitative biophysical monitoring, and remote sensing be applied at mangrove sites suspected, based upon expert opinions, to promote healthy natural mangrove forests mixed with areas of degraded and deforested mangrove forests. The primary effort must be aimed at forest characterization using data collection to determine CI and/or other quantitative measures of crown closure.

An applicable monitoring effort has begun in southwest Florida, USA on RBNERR. This effort involves the development of a rehabilitation monitoring project for 220 ha of dead and stressed mangrove forest, which has succumbed to this classification by slow degrees of degradation over the last three decades (Figs. 3 and 4, respectively). Monitoring includes limited quantitative biophysical sampling of hydrologic parameters, and the establishment and quantitative sampling of forest plots within healthy, stressed (between healthy and dead), and dead forests undergoing active hydrologic restoration. This ecological gradient mimics our understanding of the "mangrove heart attack" process. To monitor forest soil stability, we are also documenting soil surface elevation movement with millimeter-scale resolution using the rod surface elevation table-marker horizon (RSET-MH) technique (Cahoon et al., 1995), and quantifying soil benthic community structure. Not only will this document changes underway as the system degrades to the point of acute mortality (deforestation), but also track the surface elevation and benthic community changes on these sites as stress continues and/or hydrologic restoration ensues.

The specific project is referred to as the "Fruit Farm Creek Mangrove Restoration Project" (www.marcomangroves.com), and has generated lots of interest locally as residents have made clear associations between the observed mangrove die-offs and developmental modifications to local hydrology. At present it may be the only site in the US with a degraded mangrove forest that eventually will be completely deforested, and for which background information is available. The cause and dates of the degradation and deforestation are also known (Patterson, 1986; Finn et al., 1998). This provides a unique opportunity for comparison of remotely sensed imagery and signatures for a mangrove forest area in Florida known to have undergone degradation and deforestation over the last 30 years, and portions of which are currently undergoing full hydrologic restoration.

While we will be able to test our ideas associated with advanced detection and trajectories of change outlined in Fig. 2, it is clear that some measure of ecological degradation needs to be incorporated into routine



Fig. 5. Flow-chart of a proposed remote sensing and ground truthing protocol being applied to mangroves in southwest Florida (Chandra Giri, unpublished), and which can be used as a general guidance for similar monitoring efforts within coastal management plans. Abbreviations: NDVI = Normalized Difference Vegetation Index; DEM = Digital Elevation Model; DN = Digital Number; TOA = Top of Atmosphere; SSG = Spectral Similarity Group.

coastal management plans globally in order to stop mangrove losses through preemptive action. A mangrove heart attack prevention model is needed to reduce vast areas of dead mangroves over the coming decades. Prevention first starts with monitoring and detection of small degrees of degradation, identification of thresholds that may trigger acute losses, and an interest in ameliorating stresses in advance of those acute losses.

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