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Developing integrated ecosystem indices

David K. Loomis[a,*], Peter B. Ortner[b], Christopher R. Kelble[c], Shona K. Paterson[a]

[a] Institute for Coastal Science and Policy, 250 Flanagan Building, East Carolina University, Greenville, NC 27858-4353, USA
[b] Cooperative Institute for Marine and Atmospheric Studies, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149, USA
[c] Atlantic Oceanographic & Meteorological Laboratory, 4301 Rickenbacker Causeway, Miami, FL 33149, USA

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ABSTRACT

Enabling ecosystem-based management requires, among other things, reaching a scientifically based consensus with respect to the key characteristics of a sustainable ecosystem capable of supporting those levels of key ecosystem services desired by society. To determine and convey whether an ecosystem is in fact approaching this goal implies developing indicators that capture the status of both the natural and societal aspects of the system. That said, developing consistent and useful indicators for both societal and natural system aspects of the ecosystem requires both resolving disparate perspectives and inconsistent terminology between human dimensions and natural system scientists and keeping the number of indicators manageably few, without oversimplifying a highly complex ecosystem. To accomplish this we employed a "recursive relationship" approach that defined (and redefined) variables, indicators, and indices along a sliding hierarchy from measurable parameters to highly aggregated indices. To illustrate this approach it is applied herein to both a human dimensions index (recreational quality), and a natural sciences index (water column). This "recursive relationship" approach facilitated development of a parsimonious set of high-level indices that together constitute an ecosystem report card integrating natural system status and related societal dimensions from an ecosystem services perspective, while maintaining all of the information at lower levels necessary to inform specific management decisions.

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1. Introduction

The goal of the MARine and EStuarine goal Setting for south Florida (MARES) project was "to reach a science-based consensus about the defining characteristics and fundamental regulating processes of a south Florida coastal marine ecosystem that is both sustainable and capable of providing the diverse ecosystem services upon which our society depends. To achieve this goal, it was necessary to consider regional, social, political, cultural, economic, and public health factors, in both a research and management context, along with ecological variables." (Kelble et al., 2013). The MARES process built consensus at workshops consisting of scientists, stakeholders, and resource managers. These workshops developed conceptual diagrams and integrated conceptual models using the EBM-DPSER (ecosystem based management-drivers, pressures, state, ecosystem services, response) framework to capture our consensus understanding of the ecosystem, including humans (Kelble et al., 2013, Fletcher et al., 2013). The EBM-DPSER is modified from the DPSIR (drivers, pressures, state, impacts, responses) framework which has proven useful for identifying focal ecosystem components and thus ecosystem "indicators" (Bowen and Riley, 2003; Levin et al., 2008, 2009); however, the EBM-DPSER model is more consistent with an ecosystem services approach that requires "indicators" not only for natural ecosystem status but also societal characteristics and the services derived from the ecosystem (Müller and Burkhard, 2012). The former may be biological, chemical or physical characteristics. The latter may be either economic or non-economic in character but in either case are the intellectual domain not of natural system scientists but of human dimensions scientists. These limitations of the DPSIR model are also addressed in the development of the DPSWR model that replaces impacts with welfare to accomplish similar goals to EBM-DPSER (Cooper, 2013). To develop consistent and useful sets of indicators of both human and natural dimensions with respect to a complex ecosystem that is sustainable and continues to provide desirable levels of valued ecosystem services, practitioners must overcome two inherent difficulties: (1) keeping the number of indicators manageable and (2) resolving differences in perspectives and terminology between human dimensions and natural system scientists.

* Corresponding author. Tel.: +1 252 737 4263.
E-mail addresses: loomisd@ecu.edu (D.K. Loomis), portner@rsmas.miami.edu (P.B. Ortner), chris.kelble@noaa.gov (C.R. Kelble).

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To comprehensively characterize this integrated ecosystem implies a prodigious number of indicators. However, to be useful a proposed set of indicators must efficiently communicate the ecosystem status relative to societal objectives and too large of a set makes it difficult to effectively communicate both with the public and with natural resource managers (Center, 2008; Doren et al., 2009). Thus, indicator assessments that seek to encompass the holistic, integrated natural and human ecosystem must develop methods yielding a parsimonious set of indicators that communicate the comprehensive status of the ecosystem.

MARES participants encountered another inherent difficulty regarding inconsistent terminology when human dimensions and natural scientists began trying to solve the aforementioned paradox. Human dimensions scientists and natural system scientists use much the same vocabulary ("indicators", "attributes"; "variables"; "indices" etc.) but often apply these terms in divergent manners. Given the growing emphasis upon ecosystem services, the necessity to seamlessly integrate these different disciplines and perspectives has been the focus of a number of recent publications (c.f., Ringold et al., 2013; Reyers et al., 2013; Knight et al., 2013), but none of these authors directly addresses the problems posed herein. In the paper that follows we first discuss how the two very different scientific communities use the same terminology to address the indicator "problem". Differences in approach become apparent. We then suggest the approach MARES adopted toward enabling a comprehensive integrated ecosystem assessment with a parsimonious set of integrated and consistent ecosystem "indicators". This framework, which we call a "recursive relationship" (by which we mean an iterative and hierarchical relationship), is usable by both human dimensions and natural systems scientists and allowed MARES to organize their contributions into a logically consistent framework.

2. The human dimensions science perspective

The human dimensions science of coastal resource management refers to the investigation of human thought and action toward natural environments (Manfredo et al., 1996). As Vaske (2008) points out, the notion of human dimensions in resource management as described above is not that new. However, the notion of human dimensions science is new to many, including our colleagues in the natural and physical sciences. This newness and unfamiliarity can create unnecessary confusion between the natural and human dimension science communities. Although the principles derived from the scientific method are the same for us all, we have in some cases developed different approaches and terminology while essentially doing the same thing. As noted earlier, one challenge in developing consistent integrated ecosystem indices is the use of too many indicators, and another is the inconsistent terms or vocabulary used by different disciplines. A basic understanding of human dimension science terms is provided here as a step toward developing a common vocabulary that can be applied in the "recursive relationship", as is a brief discussion of the use of indices in the human dimension sciences as a way of aggregating a larger number of measures down into a smaller set of indices. It should also be pointed out that the concepts referred to below, such as attitudes, norms, satisfaction, conflict, and crowding, have been heavily researched and have strong theoretical foundations. They are not opinions, philosophy, personal values or just subjective perspectives. They are the product of decades, or more, of the application of the scientific method and theory development. There are numerous examples of how the scientific method has been applied to specific theories in order to produce valid quantitative data and allow the use of accepted and rigorous statistical tools, some of which are described in texts such as Eagly and Chaiken (1993), Ewert (1996), Fishbein and Ajzen (1975), Manning et al. (2002), Vaske and Donnelly (2002), and Vaske (2008).

Much of what is studied through the human dimensions sciences is abstract, in that the subject or issue of interest does not physically exist in the usual sense (Babbie, 2013). The human dimension sciences in general focus on abstract concepts that typically can have multiple and ambiguous meanings; concepts such as attitudes, preferences, norms, conflict, satisfaction, crowding, power, and fairness are common (Babbie, 2013). While we individually might have some notion of what each of these concepts mean, it is doubtful that we would all agree on the meaning of any of them, at least initially. For example, we all have some sense of what is meant by the ecosystem service of recreation quality. We might think of, or have heard others say, things such as I'm happy, it isn't crowded, I'm having a good time, I spent time with my family, or I caught a lot of fish. These would all seem to speak to this thing we each call recreation quality. But it is a fuzzy thing, and our individual "definitions" of this fuzzy thing can differ greatly. As a result, this splintered notion/mental image does not have much tangible use or value to managers or stakeholders.

To advance these fuzzy notions toward a more precise and agreed upon idea, human dimension scientists move through a process known as conceptualization. The numerous individual and perhaps ill-defined notions are made more specific, with definitions articulated, until the agreed upon result is a "concept" (Babbie, 2013). At that point there is agreement within a scientific community on what is meant by a term (a concept), such as recreation quality. However, this does not mean that measuring this concept is straightforward. Concepts are very complex, requiring numerous measures which in themselves can be abstract. The measures of interest we often refer to as "indicators". We mean by this an observation that we wish to consider as a reflection of a variable we wish to study. As stated they would not yet be a variable and thus not yet directly measurable. Using the concept of a quality experience for saltwater recreational anglers, we would need to include measures of catch-related motives, non-catch motives, expectations, baselines, perceived conflict, crowding, and still others. An indicator of a catch related motive would be number of fish caught, or size of fish caught. It becomes apparent that developing and communicating a *complete* (ideographic) understanding of a quality angler experience would be extremely difficult, if not impossible. The list of indicators would be long, and could seem disorganized or even random to many. Conversely, this complexity renders single measures ineffective when seeking to understand the complex and dynamic nature of such concepts. However, having a comprehensive and extensive list of indicators is equally unworkable. Both extremes (single indicators, or complete inclusion of all indicators) are less than desirable. What must be sought is a compromise that focuses researchers on including only those indicators that provide sufficient information about a concept or phenomenon (i.e., multiple measures of high explanatory value), and are in a logical and organized fashion. The goal should be not too few indicators, but not too many either.

To avoid a seemingly random list of indicators, human dimension scientists will group individual indicators into meaningful groupings (Babbie, 2013). These groupings are called dimensions. A dimension can be defined as a specifiable aspect of a concept. For example, catch motives (or their indicators) would be one dimension of a quality recreational angling experience, and non-catch motives would be a second dimension of a quality recreational angling experience. Other dimensions would include expectations, baseline, conflict, etc. Dimensions are a way of making organized sense of larger numbers of indicators of a concept. The last step is to operationalize indicators into variables and their attributes.

To the human dimension scientist, a variable is a logical set of attributes that can be measured as stated, with the attribute being a characteristic or quality of that variable (Babbie, 2013). For example, "How important is it to you to catch a large fish on your next fishing trip?" would be a variable, and 1 = not at all important, 2 = slightly important, 3 = somewhat important, 4 = very important, and 5 = extremely important would be the attributes. Variables must have two qualities: (1) the attributes must be exhaustive, and (2) the attributes must be mutually exclusive.

As noted above, it is very likely that any given human dimension science concept will be both abstract and complex. This necessitates the inclusion of a large number of indicators and variables in order to develop a meaningful understanding of that concept. Having such a large number of variables will work against any effort to present in a parsimonious perspective the comprehensive status of an ecosystem. A means of aggregating the plethora of human dimension science information into meaningful subsets is required. This can be accomplished by way of the index. An index is a type of composite measure that summarizes and rank-orders several specific observations, and represents more general dimensions. In essence, a human dimension scientist would take the responses to multiple variables from one dimension, add them together, and create one index. It should be noted that the construction of an index requires additional work, in that it must be tested and validated. A more comprehensive discussion on the construction of indices, and their testing and validation can be found in Hawkins et al. (2009) and Salz et al. (2001).

The above discussion describes how, and with what terminology, a human dimension scientist would incorporate, by necessity, a large number of variables in any examination of a concept of interest and then take steps to reduce this large number down to a manageable few for the purpose of making general statements about the status of an ecosystem and its ability to deliver ecosystem services.

Table 1
Criteria used to select indicators from the list of measurable variables within each focal ecosystem component.

(1)	Does the indicator provide an integrative measure of the overall status of the ecosystem or of essential ecosystem structures, functions or processes? (Dale and Beyeler, 2001; Levin et al., 2009; Luckey, 2002)
(2)	Does the indicator relate to ecosystem service(s)? (Feld et al., 2009)
(3)	Is the indicator relevant to management goal(s)? (Bradley et al., 2010)
(4)	Is the indicator sensitive to system Drivers and Pressures? (Dale and Beyeler, 2001; Doren et al., 2009; ICES, 2002)
(5)	Is the indicator based upon data that can be generated with accuracy and precision relatively easily and for which there is sufficient existing data to evaluate change going forward? (Dale and Beyeler, 2001; Doren et al., 2009; ICES, 2002; Rice and Rochet, 2005)
(6)	Is it possible to predict how the indicator will respond to changes in the ecosystem (including societal changes) over management-relevant time scales? (Dale and Beyeler, 2001; Feld et al., 2009)
(7)	Does the indicator have a response that is easily detectable above the background variability to make it useful in measuring response to management actions or a change in a Pressure that may or may not be a result of management action(s)? (This also means the response signal should be attributable to a change in management or pressure.) (Bradley et al., 2010; ICES, 2002)
(8)	Do managers and the public understand the indicator? (Rice and Rochet, 2005)
(9)	Does the indicator respond to stress earlier than the rest of the system (i.e. is it a leading indicator?)? (Dale and Beyeler, 2001)
(10)	How long will it take for the indicator to show a response to possible management actions? (Dale and Beyeler, 2001)
(11)	Has the indicator been employed effectively either in south Florida or elsewhere? (NRC, 2000)

3. The natural systems science perspective

The process and approach followed in South Florida Ecosystem Restoration (SFER) (Doren et al., 2009) provided a starting point for MARES, with many of the natural systems scientists contributing to that special issue of Ecological Indicators (c.f. Boyer et al., 2009; Browder and Robblee, 2009; Lorenz et al., 2009; Madden et al., 2009; Volety et al., 2009) and also participating in developing one or more of the conceptual models (c.f., Browder et al., 2005; Davis et al., 2005; Rudnick et al., 2005) that motivated the choice of the indicators discussed therein. As discussed by Doren et al. (2009) such indicators are derived from key ecological drivers and attributes, grounded in ecological theory, that provide specific information about a system and are linked to specified ecological targets. By and large the SFER indicators selected were simply "attributes" in the aforementioned conceptual models, with quantitative metrics as to the desired "target" against which a specific data value/measurement could be compared. Approaching the target represents "progress", departing from it "further degradation" from the ecosystem restoration perspective informing the SFER. A specific example will make this apparent. With respect to the indicator developed by Boyer et al. (2009), the variable measured was water column chlorophyll *a* concentration (μg/l) in specific subregions or subareas of the larger domain. The indicator was a comparison of the measured values with a "target" which was based upon the baseline observations within that same specific region. Values above the median baseline value are deemed to be at risk and values above the 75th percentile of baseline observations are deemed to be in need of management action. This last is an important point. The same concentration in a different subregion could be either an indication of restoration progress or a cause for alarm.

MARES followed a similar process; albeit focused on a sustainable ecosystem producing desired levels of ecosystem services rather than ecological restoration. The EBM-DPSER models for south Florida identified all focal ecosystem components that should be reflected in the indicator assessments. For the state box, we developed more detailed nested models within the EBM-DPSER model that included the variables that we measure (Kelble et al., 2013). These measurable variables are potential indicators that should be winnowed down to an idealized sub-set that characterizes the ecosystem status. Eleven criteria modified from previously published indicator manuscripts were used to select indicators from the list of measurable variables within each focal ecosystem component (Table 1).

It became apparent that applying these criteria to the variables within each focal ecosystem component would lead to an overwhelming number of indicators that was impractical for any application. Too many indicators would impede our ability to communicate the overall status of the ecosystem and lead to an inability to select the appropriate indicators for managing a specific component of the ecosystem. As earlier discussed, human dimensions science has a tradition of combining indicators into higher order indices (e.g., consider the widely quoted "Index of Leading Economic Indicators" popularized by the Federal Reserve). The very same approach can and for practical reasons must be taken with natural system indicators.

4. The recursive relationship: a consistent terminology and framework

To reduce the number of indicators and aggregate similar indicators in a manner consistent across both human dimensions and natural science we applied a "recursive relationship" approach. The "recursive relationship" approach combines measured variables into indicators and indicators into indices and lower order indices themselves into higher order indices, the small set of highest order indices could be used to formulate a "report card" explicable to the set of relevant stakeholders (managers, politicians,

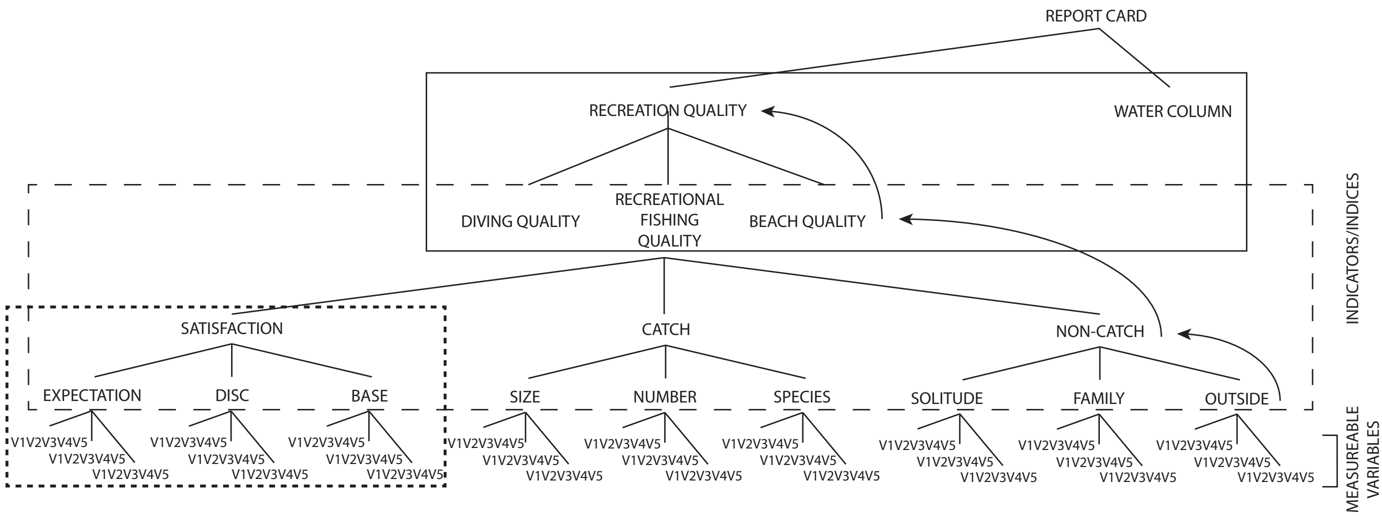

Fig. 1. The "recursive relationship" index methodology applied to recreation quality providing an example for a human dimensions index.

non-governmental organizations, businesses and interested members of the general public) (Figs. 1 and 2).

MARES defined indicators as being computed from data metrics that are defined measurements of variables, and are direct functions of those variables. It does not matter what is measured. A combination of such indicators, (and this can be a complex function where a priori weighting can be justified) we call an index. Weights, where appropriately justified, can be assigned to individual indicators (e.g., one component of an index is agreed to be of higher overall system value than another) OR can be assigned to individual geographic subregions OR can be introduced indirectly (and more subtly) through baseline comparisons as in the chlorophyll concentration example discussed above. In all cases this must be both explicit and transparent and probably should be done at the lowest possible hierarchical level. That is, indices are derived from indicators and indicators from measured variables. From here it is important to recognize and understand the recursive and hierarchical relationship between variables, indicators and indices. As noted above, variables are combined into indicators, and indicators are combined into composite indices. At the next level, indicators can be thought of as variables, which are combined into a second level of new indicators and then into a second level of new indices. This process can repeat itself in a recursive manner to the desired endpoint (see Figs. 1 and 2). An indicator may, but clearly does not have to be, associated directly with a state attribute in the conceptual model. It could be derived from a response, a driver, a stressor, a state attribute, or an ecosystem service. Looking at the relationship between these terms in this way is applicable to both ecological and human dimensions indicators. It permits both to be aggregated into indices that can be assembled into a Report Card capturing both natural system and human dimensions aspects of the marine ecosystem in a comparatively small set of "indicators".

5. A human dimensions example

Following on the recreation quality concept earlier discussed, the catch-related variables (the importance of catching large fish, catching many fish, catching a fish of a particular species, and catching a trophy fish) can each be measured on a 5-point scale. Responses to these individual variables can be summed into one composite measure (ranging from 4 to 20), with the results rank ordered from low to high. This composite measure (index) is now a single indicator/variable of the catch-related dimension of a quality recreational angling experience. A higher score would reflect a higher quality experience. A similar process can be applied to the non-catch dimension, the expectation dimension, the conflict dimension, etc. It should be noted that the terminology of dimension, index and variable is fluid, depending on the hierarchical position in the recursive relationship.

In Fig. 1, the relationship of variables to index, and then to dimension is demonstrated. Expectation is a dimension of Satisfaction. As such both Expectation and Satisfaction are abstract concepts but ones used widely in the social sciences (e.g., Mannell, 1999; Manning, 2010). In this example and position in the hierarchy, Expectation was operationalized and measured as a composite index which was composed of the 15 variables noted below it.

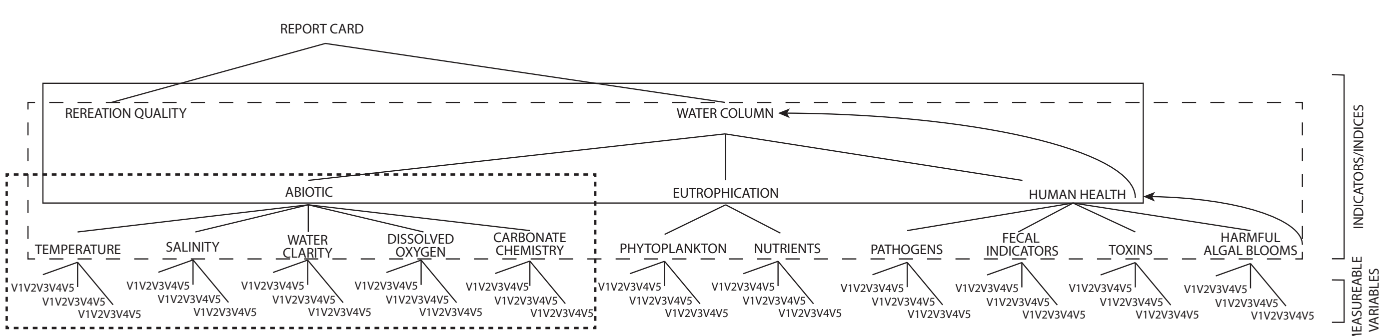

Fig. 2. The "recursive relationship" index methodology applied to the water column providing an example for a natural system index.

Similarly, Discrepancy and Baseline are also dimensions of Satisfaction, and each were measured in the same fashion as Expectation. Thus, the 45 variables (15 for each dimension) were aggregated into three dimensions of the larger concept called Satisfaction.

The next higher level in the hierarchy maintains the recursive relationship between variable, index, dimension, and concept. At the next level, Expectation, Discrepancy, Baseline, Size, Number, Species, Solitude, Family and Outside become variables. These "variables" are aggregated into indices that reflect the dimensions of Satisfaction, Catch and Non-Catch. These in turn are measures of the larger concept of Recreational Fishing Quality. The recursive relationship steps higher, with the role of variable, dimension and concept changing in a consistent manner. Exactly the same approach can be applied in the natural systems context.

An important point to be made is that any of these indices will result in a rank ordering of the combined set of variables. This rank ordering can be labeled in a number of ways. For example, the rank ordering could range from 4 to 20 based directly on variable attributes as noted earlier. Or, one could recompute that ordering into a range of 1–5. Or, it could be rank ordered as A–F, as in our report card approach. Converting the rank ordering of indices initially measured on differing metrics (which is inevitable when attempting to integrate the natural and human dimension sciences) to an A–F scale can serve to provide a common platform by which the human dimension and natural sciences can be integrated, ultimately into a final A–F report card.

6. A natural systems example

Fig. 2 depicts what we call a recursive (or repeating) relationship for a natural system report card component. The natural system component example is the coastal water column. In this analysis the coastal water column functions primarily as a supporting service for many of the other ecosystem components and the adjacent human communities. As such it is desired that the water column maintain characteristics that minimize impacts upon human health and provide the required conditions to maintain the services provided by other ecosystem components (e.g., seagrass, harbottom communities, coral, fish, shellfish, etc.). The natural system indices in an overall MARES Report Card would therefore include such a "Water Column" index. That Water Column index is derived from Abiotic, Human Health and Eutrophication indicators. From its perspective they are indicators and it is an index. That said, Eutrophication is derived from Phytoplankton and Nutrients. From its perspective they are indicators and it is an index. Consider the indicator "Phytoplankton". It can be computed from number of combinations of measured variables (for example- cell pigments, cell counts, biomass, species composition, etc.). In fact each of these can themselves be combinations of variables (e.g., species composition may include large categories like "diatoms" or "dinoflagellates" which themselves can be composed of individual species). A similar parsing can be done for "Nutrients" or "Pathogens", etc. We simply need to focus upon the relationships between the items depicted from the perspective of the combinatory levels above and below individual entities. Phytoplankton as discussed above may be derived from indicators like diatoms or cell pigments from whose perspective it is an index. Those indicators are then derived from the metrics, individual diatom species counts or individual cell pigment contributions.

As with the human dimensions example, the indices derived through this process can also be converted (rank ordered) to an A–F report card format. Doing so allows the human dimensions indices to be aggregated with the natural system indices into higher level indices.

7. Conclusions

Two challenges we face are overcoming the need to keep the numbers of indicators necessary for properly describing the status of an ecosystem and the services they provide at a manageable level, and the need to resolve differences in the terminology used by the natural and human dimension sciences. We have offered a means by which both can be accomplished.

Using the "recursive relationship approach" to yield a small set of higher order indices, MARES was able to encompass both societal and natural system aspects of a complex semi-tropical marine ecosystem having large numbers of variables and measures into a relatively small number of "indicators" that are really higher order indices. These include not only the aforementioned Water Quality and Recreational Quality but also Cultural, Historical, and Spiritual Quality; Public Health and Safety; Esthetic Quality; Educational Opportunities; Economy; Seagrass; Mangroves, Coastal Wetlands; Coral and Hardbottom; Oysters; Beaches; Water Birds; and Fish and Shellfish.

These indices constitute the template for a South Florida Marine Ecosystem Report Card. Ultimately, at the highest level we can derive one rank ordered index of overall ecosystem status on an A–F report card. While not all the measurements required to quantitatively populate this template are currently being measured, nor have all the indices themselves been developed to the extent illustrated within this volume, the template itself is useful both to establish priorities with respect to information generation and to put in perspective alternative ecosystem assessments for the same geographic domain. The recursive relationship provides to managers an overall status report, while also allowing a detailed analysis and understanding of what a particular "grade" is composed of. For example, a grade of C implies that some aspect of the ecosystem is not functioning as we would like relative to societal objectives. Through the recursive relationship managers can work down through the relationships to find which dimension is underperforming.

Our discussion also presents the similarity in approaches between the two perspectives despite differences in terminology. The scientific approach is essentially the same. The two can be integrated into combined indices, although further research is needed and indicator or index weighting will likely need to be incorporated. However, we also note that both systems are highly complex and identifying all system characteristic may never be possible, and thus efforts to identify and capture the most relevant indicators should be a priority.

Finally, conclusions derived from this integrative approach can speak to agency goals and objectives by evaluating where we are in terms of ecosystem status, and in our ability to provide desired ecosystem services. There will be tradeoffs between environmental condition and the delivery of ecosystem services. Integrating the two using the recursive relationship should allow the tradeoffs to be better identified and understood, and their trajectories reasonably predicted.

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