Synthesis of the Results of the 1997-99 STAR Ecological Indicators Grants

Deliverable 2D: Synthesis Document of 1997-1999 grants

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Submitted to

Perot Systems Government Services
31 Schoosett Street
Pembroke, MA 02359

Submitted by

FTN Associates, Ltd.
3 Innwood Circle, Ste 220
Little Rock, AR 72211

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1.0 INTRODUCTION

1.1 Background

In 1995 the Environmental Protection Agency's (EPA) Office of Research and Development (ORD) initiated a new external and independent science and technology research program - the Science to Achieve Results (STAR) program. The EPA's National Center for Environmental Research (NCER) designed the STAR program to infuse creativity and expertise into ORD through a three pronged approach: funding individual researchers through targeted Requests for Assistance (RFA); funding longer term multidisciplinary interactions through Research Centers; and stimulating the next generation of researchers through Graduate Fellowships. In the years 1996-1998 NCER announced a series of RFAs to all qualified parties to submit proposals to develop, evaluate, and integrate ecological indicators (USEPA 1996a, USEPA 1997a, US EPA 1998a).

In order for the information gathered from these research projects to be useful to decision makers, stakeholders, and the science community, it is beneficial to summarize the research results into comprehensive and easily accessible documents. In concordance with their commitment to communication, NCER is supporting a set of documents that highlight STAR program research results and successes related to ecological indicators. Because the product will be used directly by EPA, and to avoid any bias associated with the research projects, an extramural contract has been chosen as the appropriate vehicle to complete this task.

1.2 Objectives

The objective of this project is to produce three documents that outline the successes, results and findings of each of the 1997-1999 Ecological Indicators grants awarded under the RFA program: 1) a compendium of the 1997-1999 Ecological Indicators grants; 2) a synthesis of the 1997-1999 Ecological Indicators grants; and 3) a journal article based on the results of the 1997-1999 Ecological Indicators grants. The work presented here is a synthesis of the 1997-1999 Ecological Indicators grants.

1.3 STAR Program

1.3.1 Historical Perspectives

By the mid-1990s it became increasingly clear that, while EPA had made significant strides towards environmental protection, conventional approaches were yielding increasingly marginal returns (USEPA 1995). In particular, opinion was growing that traditional regulation of individual chemicals or large point sources of pollution (e.g. municipal or industrial plants) would not be effective in addressing emerging problem areas of global climate change, non-point source pollution, and habitat degradation. These new issues were perceived to be larger threats to ecological integrity than pollutants targeted by the regulatory efforts in place (USEPA 1998b). As an example of the type of situations causing concern it is widely accepted that our nation's waters are increasingly cleaner and devoid of pollution, but the number of statewide fish advisories warning the public of health risks associated with chemical contamination of some fish species has increased from to 1,233 in 1993 to 3,089 in 2003 (USEPA 2005a). This increase directly led to the EPA and the Food and Drug Administration issuing specific advice in 2004 that pregnant women and young children limit or eliminate the consumption of certain fish species (USEPA 2004). Emerging issues such as this have emphasized the need for research into understanding and combating the effects of human induced ecological stress.

Several national level reports on scientific efforts and trends at EPA clearly and resoundingly emphasized the importance of retaining a high level of science. Recommendations of these reports include that EPA make changes to strengthen the quality of scientific research, assist the nation in training the next generation of scientists, identify effects of human stressors on ecosystems, and improve communication and utility of EPA research (GAO 1988, NRC 1995, NRC 1997a, NRC 2000a).

Concurrent with this new EPA awareness of emerging issues was the enactment of the Government Performance Results Act of 1993 (GPRA, see 5 U.S.C. 305 and 31 U.S.C. 115). GPRA shifted federal agencies from accounting of processes (through dollars spent) to accounting of results (accomplishments) and introduced federal managers to the concept of transparent accountability by publicly measuring outputs and outcomes. GPRA required agencies to develop long-range Strategic Plans on 5-year cycles, produce Annual Performance Plans, and Annual Performance Reports; link these documents; and submit them to Congress.

ORD's response to these internal realizations and external events was to begin a series of planning exercises with EPA staff, research partners, and interested outsiders which culminated in 1996 with the development of an ORD GPRA Strategic Plan that was nested within EPA's five-year Strategic Plan (USEPA 1996b). In this Strategic Plan, ORD substantially shifted its research agenda and organization by aligning itself within what is now termed the *risk assessment* paradigm. EPA has defined risk assessment as,

> "…the process that scientists use to understand and evaluate the magnitude and probability of risk posed to human health and ecosystems by environmental stressors." (US EPA 1996b)

The risk assessment paradigm is a relatively simple workflow process that: A) seeks to characterize the nature of a stressor's effect; B) determines the magnitude and route of the stressor; C) combines A and B into an assessment of risk; and D) evaluates ways to reduce risk (USEPA 2001a). The risk assessment paradigm has been extremely useful to EPA as an organizing principle; however, considerable research is still needed on determining the relative risks posed by multiple stressors, at multiple scales, and on multiple endpoints (USEPA 1998b).

The 1996 ORD GPRA Strategic Plan (USEPA 1996b) was designed to be a living document (it was updated in 1997 and 2001) that focused priorities; in essence focusing on *how* ORD will assist in attaining EPA's overall core mission rather than *what* research will be done. In its Strategic Plan, ORD separated research into two distinct categories: problem driven research; and basic research that will become the building blocks of future scientific activities. The ORD Strategic Plan assigned high priority to research into improving ecological risk assessment and management and further planning efforts produced fifteen formal ORD Research Strategies (e.g. USEPA 1998b) which support and implement the ORD Strategic Plan. Each Research Strategy is designed to accomplish three goals: 1) frame scientific questions associated with important environmental issues; 2) delineate the research needs and relative priorities required to address those questions; and 3) provide the link between the ORD strategic plan and specific research plans (USEPA 2005b). The Research Strategies can be thought of as a bridge between the nested flow of strategic plans and programs goals from EPA Headquarters to ORD to individual research plans.

ORD's ultimate goal is to increase the quality and quantity of scientific understanding of environmental risk by developing more effective indicators, monitoring systems, and designs for measuring the exposure of ecosystems to multiple stressors at local, regional and national scales (USEPA 1998b, USEPA 2001a). A substantial part of the motivation for developing ecological indicators is to understand the impact of humans on the environment. However, ecological indicators are also needed as measures of performance of EPA's environmental policy as required by GPRA.

1.3.2 STAR Program

The STAR program was established in 1995 to augment EPA's research and scientific activities and improve the scientific foundations of decision making processes. The STAR program increased EPA's access to the nation's best and brightest scientists through coordinated funding to academic institutions, and has been the EPA's largest single investment in extramural research (NRC 2003). Since the STAR program's inception, it has evolved into a grant-award process that exceeds most other federal research programs by incorporating a high degree of planning in development of RFAs to ensure research and products are relevant to EPA's core mission (GAO 2000, NRC 2003). The STAR program should not be thought of as a stand alone program, but as a mechanism for EPA to accomplish the research objectives outlined in ORD's planning documents (USEPA 1996c). The process that EPA instituted to complete and issue RFAs is summarized below:

1. Begin with issues outlined in ORD Strategic Plan and Research Strategies (for examples see USEPA 1998b, USEPA 2003a),
2. Develop specific RFA and announcement,
3. Perform independent peer review of received proposals,
4. Perform internal EPA review to ensure relevance to EPA's core mission,
5. Award funding,
6. Develop annual progress reports,
7. Perform Research In Progress reviews (primary vehicle is a workshop), and
8. Develop final report.

In 2000, EPA requested the National Academy of Sciences (NAS) to independently review the STAR program. The NAS review praised the STAR program as playing an important role in EPA's research program, and made several recommendations. Two key recommendations were to 1) increase information dissemination, and 2) institute a four level review process to assess programmatic effectiveness (NRC 2003). The NAS review found that the STAR program's audience is diverse and includes other agencies, federal and non-federal scientists, laypersons, user groups, non-government organizations, and communities. The review further concluded that the program's goal of distribution of research results to diverse audiences remained a challenge that needed be addressed (NRC 2003). The NAS review additionally recommended that the STAR program consider establishing a structured schedule of expert reviews of the program at four levels: Level 1, individual research projects; Level 2, topics or groups of research projects; Level 3, the entire STAR program; and Level 4, STAR program relationships to ORD and EPA (NRC 2003). This work, and the compendium of Ecosystem Indicator RFA projects which preceded this work, should be considered as support documents to a Level 2 review.

1.3.3 Ecological Indicator RFA

In 1996 EPA issued the first of three annual RFAs specifically requesting exploratory research into ecosystem indicators (USEPA 1996a, 1997a, 1998a). In the first RFA, ecological indicator was broadly defined as "a characteristic that is related to, or derived from, a measure of a biotic or abiotic variable that can provide quantitative information on ecological structure (component networks) and function (interactions)" (USEPA 1996a). The first RFA had three stated objectives:

1. Stimulate development, evaluation and integration of indicators to improve monitoring and assessment of ecological integrity and sustainability (highest priority),
2. Develop indicators of functional processes that contribute to ecological integrity and sustainability, and
3. Develop indicators that identify effects of particular stressors of ecological integrity and sustainability (USEPA 1996a).

These objectives did not change, but rather, were refined with two subsequent RFAs that emphasized molecular genetics and landscape characterization (USEPA 1997a, USEPA 1998a) and strongly advocated scale-aware research. Of note in these subsequent RFAs was the emphasis and recognition that development of indicators incorporating multiple resource types (e.g. forest, streams, wetlands, rangelands), multiple levels of biological organization (e.g. gene, species, guild, community), and multiple geographic scales (e.g. local, regional, national) was necessary.

In combination, the three Ecological Indicator RFAs address several ORD long term research goals, most notably ORD's long term programmatic goal for ecological protection research to develop a common monitoring design and appropriate ecological indicators to determine the status and trends of ecological resources (USEPA 2005b). These ORD long term research goals echo the findings of several planning and review documents (USEPA 1996b, USEPA 2001a) that explicitly outlined that further research is required to develop the next generation of indicators for detecting ecological trends in complicated stressor-response relationships.

ORD released three additional RFA's jointly with other agencies which directly addressed ecological indicators. In 1997, ORD issued an RFA jointly with the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) to research ecological effects of environmental stressors in coastal areas (USEPA 1997b). In 1999 and 2000 ORD issued two RFAs jointly with NASA to fund Research Centers to develop programs to research ecological indicators in estuarine environments (USEPA 1999, USEPA 2000a). The products of these RFAs, while not the focus of this synthesis, certainly have assisted ORD in attaining its long term goals with respect to indicator development.

1.4 Ecological Indicators

1.4.1 Previous Research Efforts

It is necessary to place this current effort to synthesize EPA STAR program research into context with larger research efforts focusing on ecological indicators. Ecological indicators isolate key elements of the environment from an overwhelming array of signals (NRC 2000b). Niemi and McDonald provide an excellent review of ecological indicators, tracing their origins to Plato (Niemi and McDonald 2004). Ecological and biological indicators have a long tradition of use, an early example being the historic use of canaries in coal mines as biological indicators of air quality (Burrell and Siebert 1916). Recent research into ecological indicators has rapidly accelerated, in part, due to an increased need to assess ecosystem condition when making regulatory decisions (Niemi and McDonald 2004).

Within the United States regulatory framework, the National Environmental Policy Act of 1969 (NEPA) required the Council on Environmental Quality (CEQ) to submit to Congress an annual Environmental Quality Report detailing national environmental status and condition (42 U.S.C. 4341). First produced in 1970, the Environmental Quality Reports are some of the earliest examples of ecological condition reporting attempted by the United States. The quality of the reports and indicator selection were rudimentary at best, and these reports should be thought of as compendiums of easily obtained statistics (e.g. number of species listed by the U.S. Fish and Wildlife Service as Threatened or Endangered; Breeding Bird Survey data from U.S. Geological Survey) as opposed to assessments of ecological condition or trends (for examples see CEQ 1970, CEQ 1989). The Federal Reports Elimination and Sunset Act of 1995 eliminated this report (109 STAT. 709), and it was last published in 1998.

Other major regulatory reporting requirements enacted by Congress include the National Water Quality Assessment Report to Congress required by Section 305(b) of the Clean Water Act of 1972 (33 U.S.C. 1315); a comprehensive assessment of present and anticipated uses, demand for, and supply of renewable resources on forest lands required by The Forest Management Act of 1976 (16 U.S.C. 1601); and the National Park Service inventory and monitoring program to provide information on the long-term trends in the condition of National Park System resources required by the National Parks Omnibus Management Act of 1998 (16 U.S.C. 5934).

Congressional mandates such as these, heightened scientific interest, and public demand for environmental condition accounting have fueled an increase in ecological indicators research. This trend is illustrated by the fact that a 1991 literature search on research related to biological criteria yielded 210 citations (USEPA 1991), while a similar search conducted only five years later, yielded 1,962 citations (Stribling et al., 1996). Other key examples of this intensified awareness include a series of comprehensive review articles and books on ecological indicators (Adams 2002, GAO 2004, NRC 2000b, McKenzie et al. 1992, Niemi and McDonald 2004) and a new scientific journal by Elsevier, *Ecological Indicators,* which began publication in 2001. The goal of this journal is to integrate ecological and environmental indicators with management practices by providing a forum for discussion of indicator development modeling and theory, review of traditional indicator approaches, and showcasing new quantitative applications such as the use of indices (Elsevier 2005).

This flowering of ecological indicator research has produced a confusing array of definitions (for an excellent etymological review see Moldan and Billarz 1997), however, the debate over a definition actually distracts from indicator development and usage. At a basic level, indicators are signs; measured variables that have significance and value beyond what is directly observed (Moldan and Billarz 1997). Distinctions should be made between *environmental* indicators, which relate to all elements of human impacts to the environment, and *ecological* indicators, which are a smaller subset of environmental indicators (NRC 2000b). At their core, ecological indicators should describe the structure, function or composition of an ecosystem; in essence, ecological indicators should convey complex ecosystem attributes in a manageable amount of information (GAO 2004). The hope is that, through a concerted effort, research into ecological indicators will develop into tools that can forecast future environmental change, identify actions for remediation, and/or identify trends over time (NSTC 1997).

Along with the myriad of definitions, an explosion of actual indicators has occurred over a relatively short time period. A comprehensive documentation of ecological indicators available in 1996 included well over 1,000 indicators (Parker 1996) of which at least 82 were recommended for national level analysis (Emmert 1996). In a later review of ecological indicators to be used for national level decision making (NRC 2000b), the NAS used twelve criteria to winnow an extensive list of indicators down to three broad categories with the following thirteen individual indicators:

A. Ecosystems
    1. Land use
    2. Land cover
B. Ecological Capital
    3. Total species diversity
    4. Native species diversity
    5. Nutrient runoff
    6. Soil organic matter
C. Ecological Function
    7. Carbon storage
    8. Production capacity
    9. Net primary production
    10. Lake trophic status
    11. Stream oxygen
    12. Nutrient-use efficiency (for agricultural systems)
    13. Nutrient balance (for agricultural systems)

1.4.2 Criticisms

The use of ecological indicators remains partially controversial, especially in applications linking management actions to environmental trends. Ecological indicators at population or community levels are not tightly coupled with the effects of stressors, and most are “state indicators” which measure response to anthropogenic changes, as oppose to metrics which can determine exact cause-effect relationships (Niemi and McDonald 2004). Complications have also arisen from the onerous data collection requirements for measuring some indicators (NRC 2000b). Of importance is a growing consensus that integrative indicators, which assess ecosystem health, may not be adequate to measure the effectiveness of national programs like those mandated by the Clean Water Act (USEPA 2003a).

The perils of implementing ecological indicators are in part due to difficulties in communicating complex scientific issues to interested parties, which may include the general public, government officials, and/or other scientists. There is a distinct need to develop a language that can translate between scientists' and nonscientists' mental models while maintaining a technically accurate description of indicators of interest (Schiller et al., 2001). Combining several indicators into relatively similar categories or measured endpoints is one technique for aggregating indicators for the non-technical audience. An example may be combining the technical indicators of foliar chemistry, dendrochronology, crown condition, photosynthetically active radiation, leaf area index, and sub-canopy diversity into an indicator that answers the question "What is the health of the forest?" This type of aggregation is especially appealing in light of the vast quantities of available indicators, but problems remain, especially in the weighting of the merged indicators.

Several arguments cautioning against indiscriminate aggregation of indicators have been outlined (Suter 1993, Moldan and Billarz 1997, Niemi and McDonald 2004). One specific concern outlined by Niemi and McDonald is that aggregation in the form of indices, and in particular taxonomic aggregation, is a gross oversimplification of biological processes and can actually change the measured response by reducing natural variation.

Other criticisms of ecological indicators include that they do not recognize system complexity and limitation (Dale and Beyeler 2001), the lack of sound program design and implementation (NRC 1997a), and the lack of comprehensiveness of indicators (NSTC 1997). Of particular note is that in a GAO survey of 49 expert developers of environmental indicator sets found that ensuring that a sound scientific process is used to develop indicator sets was identified as a critical issue that still exists (GAO 2004).

Criticisms such as these have begun to be addressed by publications outlining how ecological indicators could be improved (NRC 2000b), developed (USEPA 1997c), or evaluated (Jackson et al., 2000). EPA's development of evaluation guidelines for ecological indicators represents a turning point in this debate, as these guidelines concisely outline how EPA should determine if ecological indicator research is based on sound science. EPA's fifteen guidelines for indicator evaluation are separated into four phases: conceptual relevance, feasibility of implementation, response variability, and interpretation and utility. These phases present a natural flow from indicator theory to application, and include specific questions that must be addressed. Efforts to increase the scientific rigor in the development of indicators have also stimulated attempts to increase scientific rigor in applying indicators in monitoring programs (Oakley et al., 2003).

1.4.3 Major Ecological Indicator Milestones

By the mid-to-late 1990s, interest in the use of ecological indicators had reached the upper levels of the United States government. Increased calls to coordinate and link ecological indicators with management actions (GAO 1988, GAO 2004) led to a National Science and Technology Council (NSTC) review of all federal monitoring and research. This review was published as a national framework to integrate and coordinate monitoring and research efforts, and was designed to identify ways to improve the effectiveness and efficiency of federal investment in environmental monitoring, which had reached an estimated $650M in 1995 (NSTC 1997). The review concluded that there was no mechanism in place to select indicators of, or report on, environmental condition or trends at the national level. As a result, in 1996 the White House Office of Science and Technology Policy commissioned the H. John Heinz II Center for Science, Economics and the Environment (Heinz Center) to develop a nonpartisan, scientifically grounded, environmental report card for the nation. Work began in earnest in 1997, when funding started, and two years of indicator selection and data gathering was begun by Technical Work Groups. *The State of the Nation's Ecosystems* (Heinz Center 2002) was published five years later and represents a major step towards an integrated system for reporting on environmental resources at the national scale. Only a few years behind the Heinz effort, the EPA announced an agency-wide “Environmental Indicators Initiative” with the goal of preparing a State of the Environment Report (Whitman 2001). EPA initiated a process very similar to that of the Heinz Center, which culminated in 2003 with the publication of the *Draft Report on the Environment* (USEPA 2003b).

Understandably, there is considerable overlap between the two reports; in fact the EPA’s document uses data generated by the Heinz report. However, there are important differences between the two documents. The Heinz Center report focuses exclusively on ecosystems, breaking the country up into six relatively mutually exclusive systems and reporting on them separately but within a unified framework. The EPA’s report focuses on a series of questions based on five broad issues related to EPA’s strategic goals (e.g. What is the quality of outdoor air in America?; What is the quality of drinking water ?). This difference in reporting goals led to the selection of different indicators, and as a result, the EPA’s report is broader, including issues of human health, drinking water quality, and air quality that the Heinz Center report does not address.

Of particular interest is that both reports repeatedly emphasized not only what was *known* about ecosystem health and trends but also what was *unknown*. In the case of the Heinz Center report, a total of 103 indicators were selected but complete data for the nation was available for only 32% of these indicators and partial data was available for 24% of the indicators. Close to 30% of the selected indicators had insufficient data to support reporting or analysis and fully 14% of the selected indicators needed further scientific development before they were ready for nationwide implementation. The EPA’s report fared no better - a total of 146 indicators were selected but complete data was available for only 30%, 70% of selected indicators lacked sufficient data to support reporting. This level of data gaps was consistent with what has been found in other current national reports (e.g. 88% of forest indicators used by the U.S. Forest Service (USFS 2004) lack sufficient data), and previous calls for better monitoring systems and design (NSTC 1997, NRC 2000b, GAO 2004)

1.5 Summary

It is against this general backdrop of research and reporting that the three STAR RFAs for Ecological Indicators have operated. As outlined above, it is clear that while ecological indicator research has been occurring for decades, much work remains. A major recommendation from the GAO was:

> “*…[That] the Chairman of CEQ develop institutional arrangements needed to ensure a concerted, systematic, and stable approach to address the challenges associated with the development, coordination, and integration of environmental indicator sets*”
> (GAO 2004).

While the EPA’s STAR Ecological Indicator RFA is certainly not a panacea, the program’s major goal is to provide basic research to develop new ecological indicators for the nation. The EPA’s effort is one of only a few national programs designed to address the need for developing indicators to support national level reporting of environmental condition. Several agencies and independent administrations, such as the Department of Interior, NASA, National Science Foundation, NOAA, and the U.S. Department of Agriculture Forest Service, have elements that research ecological indicators; however, there is no specific program to comprehensively address this need (NSTC 1997). The magnitude of work required is highlighted in the Heinz Center report which states that 14% of ecosystem indicators selected require further scientific development because there is a lack of agreement in the scientific community about how ecosystem characteristics can be measured most meaningfully and effectively (Heinz Center 2002).

The three STAR RFAs were designed to stimulate development, evaluation, and integration of ecological indicators and did not specifically charge grantees with the task of testing the final indicator with a standardized evaluation procedure (e.g. Jackson et al., 2000). The potential indicators developed by the STAR program should be considered applied research and prior to implementing these indicators in a new or existing monitoring program, considerable testing and refinement may be necessary. The widespread testing and/or adoption of an indicator developed by the STAR program is a noble desire that is currently outside the STAR program’s scope however, indicators with the highest potential for success have been identified and highlighted by this synthesis document.

2.0 SYNTHESIZING THEMES

2.1 Introduction

An overview of the products from the three RFAs, and their possible impacts, with regard to the STAR program objectives is instructive prior to attempting to understand and synthesize the research program. Metrics measuring program outputs can be quantitative and/or qualitative. While quantitative metrics can clearly be informative, they can be one dimensional and should not be used in isolation to judge any scientific program (Geisler 2000), and these metrics may not reflect the ultimate practical outcome of the research. It is exceedingly difficult to determine the effect any scientific program may have on the larger scientific community (Van Houten et al., 2000), however, in a sense, it is possible to determine if the Ecological Indicator research program is having the programmatic effects intended by ORD. We will consider the numbers of products and estimates of productivity to determine if the Ecological Indicator RFAs achieved STAR program objectives.

2.1.1 Products

A total of slightly more than $18.5M of funding was awarded by NCER for 28 proposals over the course of the STAR Ecological Indicator research program and has resulted in an impressive collection of research products (Appendix A). These products include: seven new methods; 153 articles in peer-reviewed journals; 518 presentations to user-groups, EPA staff, professional meetings, and academic institutions; and 18 new tools, models or fully functional, and populated with data, Geographic Information Systems (GIS).

The 28 grants represent a broad research effort studying all the major North American ecosystems, most biological taxa groups, and several types of stressors (Table 1, Appendix B). Overall, the research was skewed towards aquatic systems, both in the systems studied and the focus of the studies (Table 1). Analysis of the three RFAs shows that no special rankings were given to the focus areas, thus the emphasis on aquatic biota may have more to do with grantee interests, or the state of the science in disciplines related to aquatic systems. An emphasis on determining the effects or impacts of anthropogenic disturbance was also observed, and is likely due to the scientific consensus that direct modification of ecosystems and habitats by humans is the most important threat to ecological integrity. The emphasis in the 1998 and 1999 RFAs on incorporating molecular techniques for measuring genetic diversity as ecological indicators (USEPA 1997a, USEPA 1998a) is clearly evident in the summary table (Table 1). The study sites for these grants were spread across the United States (Appendix C), showing only a moderate clustering in the West, which was due to the 1999 RFA specifically stating that development of ecological indicators for western ecoregions would be given special consideration (USEPA 1998a).

Table 1: Themes/Categories for STAR Ecosystem Indicator Grants

Theme	Category	1997	1998	1999	Total
Study System	Forest	4	4		8
	Freshwater	1	4	3	8
	Freshwater/Marine			1	1
	Grassland	1			1
	Marine	1	1	2	4
	Wetlands	1		2	3
	Woodland		1		1
Focus of Study	Amphibians	1		2	3
	Bacteria	1		1	2
	Birds	1	2		3
	Fish	1	4	2	7
	Trees and forest components	1	2	1	4
	Freshwater mussels	1			1
	Insects		1		1
	Landscape	2			2
	Macroalgae			1	1
	Macroinvertebrates	2	1	4	7
	Plants		3		3
	Protists	1			1
	Soil		3	1	4
	Zooplankton	1	1	2	4
Primary Stressor	Anthropogenic disturbance	4	4	3	11
	Grazing	1			1
	Nutrients	2	1	5	8
	Pollutants		5		5
Water Quality		6	5	6	17
Genetics			5	4	9
Remote Sensing		5	2	3	10

2.1.2 Simple Metrics of Impact

Only a few methods exist to quickly and easily assess productivity of grantees. One method is to compare grantee output, measured by publications, to the well known Lotka's Law of Scientific Productivity (Lotka 1926). This law states that a very large proportion of authors produce only one paper, and a much small number of authors produce a substantial number of publications. Lotka describes the distribution as being inversely proportional, with the exponent typically being close to 2 (in essence an inverse square law). Several authors have refined this relationship and/or recomputed the exponents or constants involved - but the relationship remains (Pao 1999, Newman 2001). In a review of over 2 million papers, Newman (2001) calculated the exponent for papers published in the biomedical discipline to be 2.86. Graphically comparing the relationship described by Newman to the number of publications per STAR grantee (Appendix A) shows significant departure from the relationship described by Newman

(Figure 1). While it is possible that not every paper published with STAR funds has the individual principal investigator as an author, this strong departure from the Lotka distribution suggests that Ecological Indicator STAR grantees may be more productive than their colleagues.

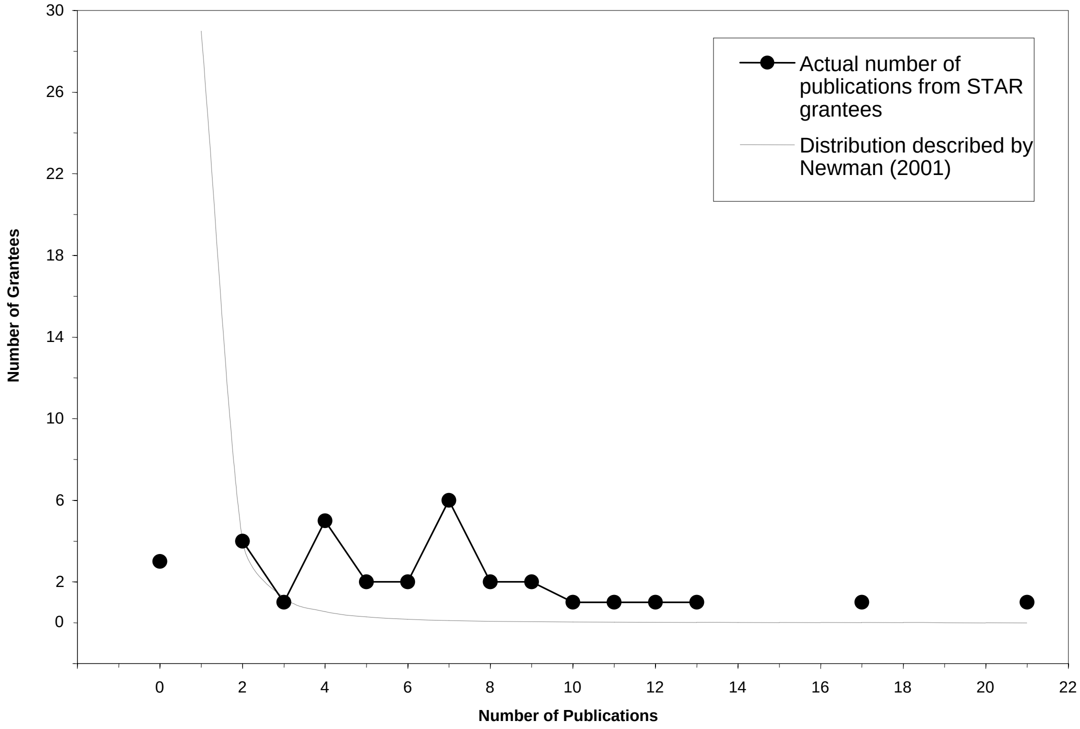

Figure 1: Predicted and actual scientific productivity of STAR Ecosystem Indicator Grants

Another easily obtained metric of the STAR program's potential impact is citation analysis through bibliometric research. This method uses large databases of published works to analyze statistics related to how often a publication is cited by other scientists. The theory is that a citation is a measure of influence in the scientific literature and an indirect indication of a published paper's impact. The independent review of the STAR program written by the NAS included a citation analysis of STAR Ecological Indicator research. This analysis showed that in 2002, citations for works published by STAR Ecological Indicator funding averaged 10.5 for 1997 STAR awardees, 8.6 for 1998 STAR awardees, and 5.3 for 1999 STAR awardees (NRC 2003). These values were not significantly different from other published research during the same years (NRC 2003). It should be noted that while papers published earlier in time might accrue more citations, the measure of a paper's impact remains fairly constant through time and only very rarely does a paper receive significant recognition after being neglected in the literature (Glänzel and Garfield 2004). This somewhat dated citation analysis indicates that Ecological Indicator STAR research is at least as well regarded by scientists as other published works.

A final, easily obtained statistic suggesting that STAR Ecological Indicator research has an impact on the greater scientific world is the fact that three of the 29 Principal Investigators (10.3%) have been identified by the Institute for Scientific Information as a Highly Cited Researcher^{TM} (ISIHighlyCited 2005). This ranking means that these scientists (John D. Aber, K. Ramesh Reddy, and Monica G. Turner) are among the 250 most cited researchers in their respective fields for their published articles. While the STAR funded research can not be considered solely responsible for this honor, this clearly shows progress towards the ORD goal for the STAR program to infuse new vigor into EPA's research by attracting the nation's best and brightest scientists to tackle research problems.

2.1.3 Synthesizing themes

The projects funded by the STAR Ecological Indicator research program can be categorized into four broad topics, described as questions for convenience. These questions are based on an April 2001 STAR Research Capsule (USEPA 2001b) and correspond roughly to both the stated goals and objectives of the three RFAs, and the type of research ultimately funded. Several of the 28 grants address one or more of these questions (Appendix B) and these four unifying questions will form the basis for the following synthesis of the STAR ecological indicator research.

1. How can we identify and develop molecular and cellular indicators for monitoring and assessing changes in genetic diversity in response to environmental stress?

2. How can we relate indicators of population and community structure and function to exposure to chemical, physical and biological stressors?

3. How can we assess ecological condition through chemical indicators?

4. How can we use remote sensing techniques to develop landscape indicators that quantify and characterize the geographic extent of key attributes as they relate to a range of environmental values?

2.2 Genetic diversity responses to environmental stress

2.2.1 Introduction

Genes are hereditary units composed of sequences of deoxyribonucleic acid (DNA). A collection of genes forms an organism's genome - what is commonly referred to as the *blueprint of life*. The role of DNA is to provide cellular level instructions (transcription) to messenger ribonucleic acid (mRNA) for creation of the proteins (translation) that carry out all aspects of cell function and structure. Alleles (series of genes or DNA segments) can exhibit incredible variation within a species population, and the physical manifestation of an organism's unique genetic combinations (genotype) is termed the phenotype.

There are four main forces that maintain genetic diversity at the species level: mutation, migration, selection, and genetic drift. Mutation is the ultimate source of genetic diversity, but is typically a weak force for maintaining genetic diversity as it acts over extremely long time periods and most mutations are either lethal or neutral, thus conferring no added ability to survive. Changes in population migration patterns can have a strong effect on a species genetic diversity, and generally increase diversity within populations while homogenizing diversity among populations. Selection (natural or otherwise) is the preferential survival of individuals based on inherited characteristics, and can also have a strong effect on genetic diversity, depending on the form of selection operating. Genetic drift is random shifts in allele frequencies that occur in a finite population. Genetic drift effects are strongest in small populations where a limited number of breeders set the genetic stage of a population for succeeding generations. Genetic drift, along with associated processes such as *population bottlenecks* and the *founder's effect*, tend to decrease diversity in a population and increase diversity between populations. Since genetic diversity is shaped by these four genetic forces, it is possible to reconstruct the evolutionary history of a species by analyzing the genomes of several individuals within a population.

Human caused environmental stressors can affect genetic diversity by altering the direction and/or strength of genetic selection forces, thus genetic indicators have been suggested as a potentially useful indicator whose response is multigenerational, spanning years and/or decades. The central hypothesis of using changes in genetic diversity to measure responses to environmental stress is that environmental stressors change the survival and/or reproductive rates of some individuals and thus ultimately change the magnitude and/or direction of natural selective forces. Comparing genetic indicators from two populations, one under environmental stress and one not, can thus be used to measure anthropogenic impacts.

The scientific literature has documented links between individual stressors and genetic diversity (reviewed by Bagley et al., 2002) and currently, cause and effect relationships have been established for only a few species and a limited number of chemical stressors. A unified picture has not yet emerged and the use of genetic diversity as an indicator remains to be proven, especially with respect to anthropogenic stressors. It is important to clarify that while some stressors have been shown to affect genetic diversity of some species, the link between genetic diversity and the ultimate survival of a species is largely unproved. Conservation biology theory dictates that low genetic diversity of a species creates a situation where only a few alleles can be selected upon, resulting in a population in which adaptation to change is slow and inefficient. Inbreeding depression is the loss of fitness (i.e., the number of offspring) due to lowered genetic diversity. The *extinction vortex* model (Gilpin and Soulé 1986) carries this concept further by predicting that as a population's fitness decreases a further decrease in genetic diversity results, which leads to an even lower population fitness. This negative feedback loop can continue until extinction. However, there currently is a paucity of empirical evidence that supports the theory that genetic diversity is related to long-term species survival or adaptive ability (Bagley et al., 2002).

Two different sampling designs are used in determining genetic effects of stressors: control-impact studies and regional studies. Control-impact studies compare genetic indicators from sites with known exposures to stressors to those from reference sites. Regional studies use a large number of sites to create a regional genetic profile of a species. The following stressor effects on genetic diversity described by Bagley et al. (2002) form the theoretical basis for much research into genetic diversity indicators:

a. Habitat Loss → Decrease dispersal and/or breeders → Increases in genetic diversity among populations and decreases within populations.

b. Habitat Degradation → Decreased population size → Decreases in genetic diversity within populations.

c. Introduction of new species → Hybridization or competition → Increases in genetic diversity if hybridization or decreases in genetic diversity if competition.

d. Mutagens → Increases mutation rate → Increases in genetic diversity.

If these predictions hold true, it should be possible to attribute changes in any of the four genetic forces to ecological condition. For example, with correct sampling design and appropriate sample numbers, it should be possible to measure changes in the mutation rate within a population's genome in response to contaminants.

Until recently, measurement of genetic diversity has been limited to indirect methods of measuring individual morphologies (phenotypes) by natural historians and taxonomists. Prior to the invention of the polymerase chain reaction (PCR) in 1983 by Kary Mullis, genetic diversity could only be measured at the molecular level indirectly using allozyme electrophoresis. This technique, developed in the 1970s, maps out the speed with which enzymes (proteins) travel under electrical current. Enzymes that differ in their speed of travel are a result of allelic differences at a single gene and are called allozymes. The method is an indirect measure of the genome because it measures the output of DNA (i.e., proteins) not DNA itself.

Newer molecular techniques are direct measures of genetic characteristics of DNA. PCR is a method that amplifies the DNA found in cells and produces enough DNA to support quantitative analysis. PCR requires the development of primers – short artificial DNA strands that exactly match the beginning and end of a DNA fragment to be amplified. If DNA is present that matches the primer being used, amplification results. Inside the body, there are two different sources of DNA. The most common source is nucleic DNA (typically abbreviated nDNA or simply DNA). In addition, there is a much smaller amount of DNA found in mitochondria (mtDNA). A principal advantage of using mtDNA is that it is inherited only from the mother and thus is very stable over generations.

Since the invention of PCR, a proliferation of molecular analytic techniques has occurred. They are briefly summarized below.

- Microsatellites: Microsatellites are extremely variable regions of the genome and come in three variants: simple sequence repeat (SSR), short tandem repeat (STR), or variable numbers of repeats (VNTR). Very short genetic segments are repeated in the genome microsatellites and the length of this repeated sequence can be used to test genetic differences.

- Restriction Fragment Length Polymorphism (RFLP): In this analytic technique DNA is amplified by PCR and then chopped into restricted fragments using enzymes. Locations cut by an enzyme vary between individuals from the same species, indicating genetic differences between the individuals (polymorphism). This technique requires the development of a genetic library.

- Random Amplified Polymorphic DNA (RAPD): In this technique DNA is amplified by PCR using short random primers to amplify many DNA regions (typically 10-50). This technique is usually applied when little is known about a species genome. The pattern of DNA fragments that are present is polymorphic, resulting in the ability to test genetic differences.

- Amplified Fragment Length Polymorphism (AFLP): AFLP is a variation of RAPD where a genome is first cut by restriction enzymes and then amplified using PCR. The primers used consist of a longer fixed portion and a shorter random portion of DNA, making this a very sensitive method for detecting polymorphisms.

- Chromosome Walking: This is a PCR based technique that uses a multi-stage process to sequence chromosomes (long DNA strands). The method starts at a known location on the chromosome, using a primer reproduce a segment of the chromosome (sequence). The ending section of that sequence is used as the beginning primer for the next sequence, thus the method systematically moves along a chromosome mapping overlapping sequences.

2.2.2 STAR Grants

Eight Ecological Indicator grants addressed genetic issues in some way, with some grants using several techniques to answer more than one genetic question. Two of the grants used molecular biological techniques to develop indicators of biological diversity, one grant used genetic information to investigate demographic patterns, three grants examined genetic damage through changes either caused by mutations or chemicals that damage DNA (and are thus termed genotoxic), five of these grants studied genetic diversity using control-impact studies, and three of these grants performed experiments to test fitness response to alterations of genetic diversity (Table 2).

Table 2: Summary and status of genetic indicators tested and/or developed by STAR Ecosystem Indicator Grants

Grant	Biological Diversity	Demographic Effects	Genetic Damage	Control / Impact	Fitness response	Indicator ready for EPA review
R82-6593				X	X	
R82-6596		X			X	
R82-6599				X		
R82-6602			X	X	X	
R82-6603			X	X		
R82-7639	X					X
R82-7643			X	X		
R82-7641	X					

Biological Diversity

Two grants (Table 2) used molecular techniques to develop indicators of biological diversity. In these grants the researchers were interested in determining the bacterial population structure of an ecological system. Both grants used the DNA sequence of the 16S rDNA gene, which is present in most forms of life and is well documented by evolutionary scientists, to determine the species of bacteria that are present in water (R82-7639) and soil (R82-7641). Both studies were extremely successful in their application of the technology and R82-7639 made several significant original contributions to genetic science (see below).

Grant R82-7641 used RFPL to determine bacterial diversity impacted and unimpacted wetland sites. Clear differences between the sites were evident and certain bacterial groups were higher in impacted regions. Nutrient enrichment in impacted sites (especially phosphorus and nitrogen) was discovered and is suspected to cause the shift in bacterial communities.

Demographic Effects

One ecological indicator grant (Table 2) developed a novel PCR based chromosome walking technique to investigate the role genetics play in the reduction of reproductive success in small populations of the wildflower Perennial Lupine (*Lupinus perennis*). Six genetic markers were isolated and examined in the 10 populations studied. This study found that individuals from small populations had significantly lower allele variation at the marker sites. Other genetic testing showed that the smaller populations tended to self pollinate more frequently and that seeds in larger populations had a greater number of fathers than seeds from small populations. Data from this study gave strong suggestions on three fronts that genetic diversity may decrease in small populations.

Genetic Damage

Three ecological indicator grants (Table 2) examined genetic damage either through changes in mutation rates or short-term genotoxicity of compounds. In all three studies, genetic damage was determined to be the result of contaminants. In the first grant (R82-6602), concentrations of four (Cr, Fe, Mn, Ni) out of eight metals tested in dandelion (*Taraxacum officinale*) leaves were found to be significantly correlated to an increase in single-event mutations (measured by VNTR variation) across 29 study sites in five states. It should be noted that in no case did this study find a correlation between mutation rate and soil concentrations of any metal tested.

The second study (R82-6603) was successful in supporting only part of its central hypothesis of the genotoxic effects of pesticide laden waters. Timed exposure to pesticide laden water in the field and laboratory was not shown to affect acetylcholinesterase enzyme activity (a nerve enzyme that is targeted by organophosphate and carbamate pesticides) in Sacramento suckers (*Catostomus occidentalis*). Further genetic testing of fish tissues produced similar results; the number of DNA strand breaks was not related to the timed exposure of pesticide contaminated waters. However, the number of DNA strand breaks did show a relationship with storm events. This indicated that genotoxic effects were being caused by toxic substances delivered via storm runoff, but not any of the 31 pesticides tested. Additional testing eliminated metal contamination as the source of mutagenicity, thus other contaminants likely caused the observed effects. This grant also compared RAPD and AFLP methodologies and found that results obtained from AFLP techniques have far superior reproducibility to RAPD techniques. This key finding on the superiority of AFLP was later incorporated into EPA ORD plans and strategies (Bagley et al., 2002).

In the third study (R82-7643) rainbow trout (*Oncorhynchus mykiss*) were placed in cages for 48 hours in 16 lakes that exhibited a wide range of habitat degradation and/or recreational activity. Changes in proteins encoded (gene expression) by eight genes were measured in the trout mRNA. Levels of specific compounds (e.g. polycyclic aromatic hydrocarbons (PAHs), mercury) were below detectable limits and thus can not be linked to genetic change however, recreational activity was significantly correlated to in changes in expression of three genes.

Control-Impact Studies

Five ecological indicator grants (Table 2) studied genetic diversity using control-impact studies. Across all studies, a total of 13 species were tested with mixed results (Table 3) with genetic differentiation correlated to anthropogenic impacts for 10 of these species. These results showed that, for the most part, some type of genetic force (e.g. artificial selection) is acting to change the genetic makeup of populations in impacted areas. Analysis additionally confirmed that many detected anthropogenic genetic impacts resulted in a negative impact on genetic diversity (i.e. reduce diversity). However, it is of particular interest that, of the 13 species tested, seven showed either no effect, or a positive effect on genetic diversity (i.e. increased diversity) from anthropogenic impacts. These results are counter to the prevailing scientific opinion that pollution *reduces* genetic diversity. Conflicting results found by these studies could arise from any of a number of causes (e.g. species choice, experimental design, sample size, genetic marker choice, genetic test employed) which are all very difficult to quantify.

Table 3: Results of control-impact studies from genetically based STAR Ecosystem Indicator Grants

Grant	Method	Species	Impact Detected by Genetic Differentiation	Impact's Effect on Genetic Diversity
R82-6593	Allozyme and mDNA	Mummichug – Fish *Fundulus heteroclitus*	Yes	None
R82-6599	RAPD	Rusty Crayfish – Crustacean *Orconectes rusticus*	Yes	Reduction
		Tadpole physa - Snail *Physella gyrina*	Yes	Reduction
		Damselfly – Insect Order *Odonata*	Yes	Increase
		Earthworm – Worm Phylum *Annelida*	Yes	Reduction
		Pillbug – Invertebrate Order - *Isopoda*	Yes	Increase
		Pacific Herring – Fish *Culpea pallasi*	Yes	Reduction
		Amphipod - Amphipod *Hyalella azteca*	Yes	Reduction
		Garlic mustard – Plant *Alliaria petiolata*	No	
R82-6602	VNTR	Dandelion – Plant *Taraxacum officinale*	Yes	Reduction
R82-6603	RAPD and AFLP	Sacramento sucker – Fish *Catostomus occidentalis*	No	
R82-7643	mRNA and AFLP	Signal Crayfish – Crustacean *Pacifastacus leniusculus*	No	
		Lahontan redside–Fish *Richardsonius egregius*	Yes	Unknown
		Speckled Dace - Fish *Rhinichthys osculus*	Pending	

As a whole, results from these studies confirm that much work is needed before genetic diversity could be considered a robust ecological indicator, and that the recommendation of Bagley et al. (2002), that genetic diversity be used as only one component of a multi-indicator assessment, is still valid.

Fitness Response

Three ecological indicator grants (Table 2) examined the response of fitness to alterations of genetic diversity. Two grants designed experiments to investigate the ramifications of a decrease in genetic diversity by exposing test species to clean and contaminated laboratory settings for several generations and measuring a variety of demographic parameters and one grant used standard natural history techniques to investigate fitness responses to small and large source population sizes.

Grant R82-6593 showed that two generations of mummichug rearing in clean or contaminated water produced no evidence suggesting that pollution tolerance and the associated change in genotype affected measures of fitness (e.g. growth, time-to-maturity, and fecundity). Grant R82-6602 documented that dandelions differ in their competitive ability (as measured by six productivity measures) when grown on contaminated and clean soils. Artificial selection created a competitive difference in populations such that dandelions from contaminated areas excelled on contaminated soil, and dandelions from clean soil excelled on clean soil.

Grant R82-6596 used traditional life history techniques to show that inbreeding depression caused by small population sizes in wild lupines affected seed abortion, seed production, seed emergence, seedling survival, and seedling biomass. The results from these three studies add to the growing body of research on the ultimate consequence of pollution induced genetic change.

Indicator ready for EPA Review

Ecological Indicator grant R82-7639 developed a new assay to indicate fecal contamination of water based on using molecular markers to detect *Bacteroides* (a genus of anaerobic bacteria that are found in the guts of many species). This novel application of the principles of PCR dictated that if the primer used matches any DNA found in a water sample, amplification results. Thus, if amplification occurs, the water samples contain bacteroides associated with that primer, indicating the presence of fecal contamination. Since bacteroides species are host specific, sources of fecal contamination can be identified using this analysis. This grant created two new primers specific to bacteroides found in mammals (elk and dogs) and used several existing primers for bacteroides found in other animals (cats, cows, pigs, humans) to amplify unidentified DNA fragments found in water samples. This new assay technique has three major benefits over traditional measures of fecal coliform contamination: 1) It detects fecal contamination in 3-4 hours, significantly faster than the days it takes with traditional measures; 2) The new assay can distinguish between human and animal sources and determine the host species, which most previous methods could not; and 3) The new assay is four orders of magnitude more sensitive than previous measures.

This new ecological indicator funded by the STAR program can support the ORD goal of providing timely and accurate information to municipal officials to protect human health, and is one of several indicators discovered by the STAR program that are ready to be fully implemented. While the STAR program has not formally adopted a methodology to test or evaluate potential indicators, this indicator can and should be tested using EPA’s methodology (Jackson et al., 2000) prior to widespread adoption.

2.2.3 Summary

In conclusion, the STAR Ecological Indicator grants investigating effects of environmental stress on genetic diversity have made significant progress on many fronts.

Cutting edge molecular techniques have been developed and original contributions by STAR grantees have increased our knowledge of the effects of environmental stress on genetics. In one case, research has progressed to the stage where an ecological indicator is ready to be formally evaluated (R82-7639). However, overall, the results of the STAR sponsored research suggest that genetic diversity should not be applied indiscriminately as an ecological indicator and that much research is still needed to standardize genetic techniques and experiment design to ensure the desired results are achieved.

2.3 Population and community structure responses to stressors

2.3.1 Introduction

The measurement and assessment of biological response to anthropogenic stressors can be classified into categories of increasing complexity: demographic response of one or more species; simple community indices; multivariate indices; and multimetric indices. Demographic responses to stressors are one of the simplest and more direct forms of understanding stressor response and take the form of analyzing alterations of life history traits, such as in reproductive output and body condition and is typically applied with one species. Simple community indices begin to take into account population biology and try to measure stressor-caused changes to complex ecosystem biodiversity patterns by using simple statistics such as species richness or species diversity. Sophisticated multivariate indices attempt to link large biological community datasets with environmental condition data through multivariate correlation analysis. Multimetric indices consist of a number of different indicators (metrics) that are sensitive to anthropogenic stressors and are combined into a single value.

The use of biological communities to measure human impact on the environment stretches over 150 years (Davis 1995) and has evolved from purely qualitative speculations of early 17th century naturalists to sophisticated quantitative models. Much of the oldest environmental impact research was tied to investigating effects of water pollution on aquatic life, which began in the formative years of regulatory biology (Davis 1990). A numerical index based on freshwater worms was introduced in 1933 by Wright and Tidd and is considered to be one of the first attempts to quantitatively characterize ecological condition (Davis 1995). However, the use of this index remained in the hands of a small set of qualified experts, not regulatory agencies, a criticism that is valid for many bioindicators used today (Dale and Beyeler 2001, GAO 2004).

Simplified community indices that went beyond correlating the total number of organisms in an area to water quality assessments were based upon information theory and first appeared in the 1960s (Davis 1995). The Shannon-Wiener diversity index was the first of these new indices to be used in biological assessments and takes into account both the abundance of a species and the number of species. This and other easily calculated values such as *Evenness* and *Dominance* rapidly became popular endpoint measurements (NRC 2000b). Popularity of these indices has been strongly criticized (Metcalfe 1989, Cairns and Pratt, 1993) on the grounds that there is little ecological significance to these measures, errors are not system dependent but dependent on the type of sampling schemes used, and these measures lose biological information by representing biological communities with a single value. The joining of quantitative methods with ecological significance culminated in a Biotic Index (Hilsenhoff 1977) in which the number of individuals of a species is weighted by a pollution tolerance factor. Later revs ions of biotic indices became extremely popular with water quality assessment programs, especially the development of a family-level index (Hilsenhoff 1988) that could be implemented by minimally trained staff.

The Index of Biological Integrity (IBI) (Karr 1981) was introduced shortly after the Hilsenhoff's Biotic Index and employs a somewhat different methodology to assess aquatic condition. The IBI is not an analysis of a biological community, but instead a multimetric index that analyzes several hierarchical levels of biology using a sample of the community assemblage (Simon and Lyons 1995). The original IBI combined 12 warm-water stream fish community attributes (metrics) into a single value. The attributes used in this IBI included fish species richness, abundance, condition, trophic status, reproductive traits, and indicator species status (number of species and individuals of sensitive species). The multimetric IBI has been subsequently modified for other taxonomic groups such as macroinvertebrates (Kerans and Karr, 1994) and birds (O'Connell et al., 2000). The multimetric approach to biological assessment is not without critics (see Suter 1993 for an excellent review), but it has been widely accepted by the regulatory community and some variant is now used by regulators in all 50 states (ITFM 1995, USEPA 2002).

Criticisms of the multimetric approach can generally be addressed by ensuring that sound scientific principles are applied during the development and testing phase of bioindicators (Jackson et al. 2000). A review of the multimetric indices developed for the Mid-Atlantic Integrated Assessment (MAIA) study generally supported linking human disturbances to biological change, with certain reservations (Fore 2003). Fore (2003) found that submitting candidate metrics to multiple tests safeguarded multimetric indicators from circular reasoning. The search for acceptable metrics is time consuming, for example in the case of the MAIA study, only 15% of 58 fish candidate metrics and 6% of candidate invertebrate candidate metrics were left after a rigorous winnowing procedure. Fore (2003) also found that caution should be exercised when linking disturbance to biological endpoints, as 73% of 60 reference sites identified based on best professional judgment failed to meet independently established criteria for reference condition. This critical disconnect between professional judgment and reality seriously hampered scientific inference in MAIA and should be considered in the development of any new bioindicator.

2.3.2 STAR Grants

Seventeen Ecological Indicator grants addressed populations or community structure in some way. Six grants tested or developed life history indicators, seven examined simple community indicators, two used multivariate techniques to assess environmental change, and four either tested, or developed multimetric indicators (Table 4). Of the seventeen grants, two are extremely promising or are ready for a formal review and one (R82-5869) has already undergone a rigorous self review and is in the final stages before being ready to be implemented by EPA.

Table 4: Status and summary of types of population/community structure indicators developed by STAR Ecosystem Indicator Grants

Grant	Life History	Simple Community	Multivariate	Multimetric	Promising or ready for EPA review	Indicator ready for EPA Implementation
R82-5866				X		
R82-5867		X				
R82-5868			X			
R82-5869		X				X
R82-5870			X			
R82-5871		X		X	X	
R82-6591	X					
R82-6595	X					
R82-6596	X					
R82-6597				X	X	
R82-6598	X					
R82-6600		X				
R82-6602	X					
R82-7640				X		
R82-7641		X				
R82-7642		X				
R82-7643		X				
R82-7644	X					

Life History

Six Ecological Indicator grants (Table 4) tested or developed life history indicators. The difference between success and failure of life history indicators seems to be related to biological complexity – indicators built on simple life history indicators of one species were successful and multi-species indicators (R82-6598 and R82-7644) produced mixed results. In R82-6598 an indicator based on the reproductive success of many bird species were combined and relationships with quality of habitat. Grant R82-7644 looked at egg production of four zooplankton species groups. Neither of these multi-species indicators was successful in developing strong relationships between effect and response. All other life history indicators investigated in the STAR grants were relatively successful in determine a relationship between effect and response and these indicators were based on straightforward life history traits. The four successful indicators included: developing a lake transparency indicator based on body size of zooplankton (R82-6591); determining the trade-offs of pollution tolerance and productivity growth, time-to-maturity, and fertility of fish (*Fundulus heteroclitus* R82-6595) or plants (*Taraxacum officinale* R82-6602); and investigating affects of source population size on seed production, seed emergence, seedling survival, and seedling biomass of *Lupinus perennis* (R82-6596). Indicators with strong relationships all showed stressors negatively affecting demographic parameters.

Simple Community

Seven Ecological Indicator grants (Table 4) examined simple community indicators, with varying degrees of success. Three grants developed successful indices of presence/absence of species: two looked at frogs and toads (R82-5867 and R82-7642) and found that the presence of frogs and toads was linked to broad landscape variables, such as presence of woodlands, but not site specific or local variables; and the third (R82-5871) found that the absence of freshwater mussels is good indicator of urbanization of Midwestern streams.

Two grants (R82-5867 and R82-6600) looked at relationships among species richness, scale, and biotic communities. In grant R82-5867, frog and toad species richness was found to be only related to broad landscape variables, and invertebrate species richness was found to be negatively associated with agricultural landscapes. Avian species richness was found to be moderately associated with distance to floodplain forests, and not specific vegetation types or communities (R82-6600).

Two grants (R82-5871 and R82-7643) tested biotic indices for benthic invertebrates and zooplankton (e.g. abundance, richness, and several different tolerance indices) with none of indices tested corresponding very well to areas impacted by humans. One grant (R82-5871) tested a suite of ten commonly used biotic indicators (e.g. Hilsenhoff family-level, proportion of filterers/collectors, dominant two taxa). In this grant, poor correlations between traditional biotic indices and human disturbance seemed to be related to both the poor characterization of reference conditions and high yearly variation.

Finally, another grant successfully developed the FORAM Index (R82-5869), a new biotic index for marine water quality and coral reef habitat assessment based on the relative proportion of foraminfera (shelled single celled organisms) present in sand samples (see below). This new biotic index has been evaluated using the EPA methodology (Jackson et al. 2000) and was found to be an excellent indicator with wide applicability to coral reef areas around the world.

Multimetric Indices

Two grants (R82-5871 and R82-6597) investigated potential applications of traditional multimetric indices of integrity, while two different grants (R82-5866 and R82-7640) attempted the difficult task of developing new multimetric indices. Ecological Indicator grant R82-5871 tested correlations between the degree of urbanization in a watershed with the stream macroinvertebrate benthic (B-IBI) and the qualitative habitat evaluation index (QHEI). The QHEI is a multimetric index that combines six variables that characterize stream physical processes to provide an assessment of watershed land use practice and disturbance of stream habitats. Both the B-IBI and QHEI were found to be strongly correlated to the percent of a watershed that is covered by impervious surfaces such as concrete or asphalt. The results of this grant suggest that the percentage of a watershed with impervious surfaces could be an indicator of biological integrity as measured by both fish and stream condition as measured by instream geography.

Ecological Indicator grant number R82-6597 explored relationships of land use and landforms with four multimetric indices: a regionally calibrated IBI, the Invertebrate Community Index (ICI), EPA Habitat Assessment Protocol (EPAHAB) and NRCS Stream Visual Assessment Protocol (SVAP). A comprehensive suite of field, GIS, and remotely sensed based variables were collected with hundreds of variables screened as potential indicators. The time required to collect these variable was wide-ranging; some required intensive field work and analysis by technical experts (e.g. macroinvertebrate counts), others required field work by non-experts (e.g. habitat evaluation); others no field work but analysis by technical experts (e.g. land use classification if remotely sensed data); and others no field work and existing data (e.g. GIS datasets such as elevation or stream courses). Models built upon variables requiring GIS data and field work by non-experts were termed *management models* and explained a high percentage of variation in several indices of biological integrity. Fourteen management models were identified that could successfully predict any of the four targeted multimetric indices. Management models represent an extremely cost effective potential assessment methodology. Interestingly, this study produced results which contradict prevailing scientific thought; recent land cover change metrics were more useful in the multimetric models than the use of historical land use data. This grant also developed thirteen different models based solely on GIS data (and thus require no field data) and determined that while predictive power is low (60-80%), these models could successfully predict aspects of the four multimetric indices. As a group, individual management models were better predictors of multimetric indices than multivariate models that require no field data, however, on average, the loss is minimal, 7% of the explained variance. The suite of models identified as predicators of ecological integrity need further testing and refinement prior to evaluation by EPA.

Two grants attempted to develop a new multimetric index (R82-5866 and R82-7640), and both grants focused geographically on the Mid-Atlantic Highlands (MAH). The multimetric index Headwater Stream Assessment (HSA) developed by R82-5866 was based on forests, stream condition, and stream acidity and the multimetric Stream Plethodontid Assemblage Response (SPAR) developed by R82-7640 was based on community analysis of salamander populations (R82-7640). The HSA was developed to assess environmental response to three different stressors: percent forest cover was used to assess terrestrial habitat fragmentation; stream condition was used to assess stream habitat; and pH was used to assess acidification of streams caused by deposition or coal mine drainage. Measurements of these three variables are ranked according to severity of response and the three bioindicators are averaged to calculate the HSA. The weak relationships with most of the factors examined by this grant preclude its general use.

Initial testing of the SPAR under grant R82-7640 began with defining reference, non-reference and degraded stream criteria and testing 33 separate salamander population metrics against these conditions. Defining stream criteria was difficult, a problem commonly reported in the scientific literature. Most of the difficulty was traced to strong correlations of criteria with the latitude of the stream, indicating regional differences not related to stream condition. Sophisticated statistical techniques could not correct all these influences. As an interim measure, the 138 streams evaluated were grouped into three geographic regions for classification. The relationships of the 33 salamander metrics to stream condition were then evaluated for each geographic region. Only 11 metrics were deemed of potential value, and the best SPAR (which combined salamander species richness with number of larval salamanders) correctly classified only 76% of the stream types. Unless the issues surrounding the characterization of stream sites are resolved, the utility of the SPAR within the MAH is limited. This indicator will require further testing and refinement to be of use in other regions of the United States.

Indicators ready for EPA Review

Three grants have produced indicators showing enough promise that EPA should consider pursuing further indicator development or refinement. The study by R82-5871 of impervious surface as an indicator should be considered as a part of a larger body of scientific research of the effects of urbanization on receiving water bodies (see Arnold and Gibbons (1996), CWP (2003)). This indicator has enormous potential due to its ease of collection in large areas. Given the increasing role humans play in the environment, a successful indicator of degradation caused by urbanization would have considerable impact towards realizing EPA's goal of monitoring status and trends of ecological resources. Several programs directed by key offices within EPA (e.g. Office of Water, Office of Research and Development) are actively researching impervious surfaces as a potential indicator and while a cohesive picture is emerging, further research remains to unify this theory into a practical indicator.

Research into predicting complex biological processes such as biological integrity using simple elegant models which require little or no field work (R82-6597) also show enormous potential in assisting EPA attainment of environmental goals. Although predictive power of the indicators using no field data was relatively low (60-80%), using simple field techniques generally improved performance. The basic trade-off between accuracy of modeling and rapid, cheap data collection should be investigated further by EPA.

Finally, one indicator (FORAM Index R82-5869) has been evaluated by the principal investigators within the context of EPA guidelines (Jackson et al., 2000). The FORAM index is well developed, is one of only a handful of successful indicators of coral reef habitat potential, and is perhaps the only such indicator that is independent of coral populations. The FORAM Index has been tested at four sites worldwide and has wide regional applicability. This index can determine if decline in coral dominance on a reef is due to nutrification or episodic stress events, such as temperature extremes or hurricanes. A fascinating aspect of this biological indicator lies in its ability to be applied to reef sediments, extending the analysis time scale backwards several decades. The extensive scientific testing of this indicator has proved its usefulness and this indicator is ready for wide spread use.

2.3.3 Summary

In conclusion, the STAR Ecological Indicator grants investigating measurement and assessment of biological response to stressors have made significant progress on many fronts. Taken as a whole, Ecological Indicator sponsored research seems to indicate that simple indicators of community ecology have a stronger correlation with responses than more complicated, multi-species indicators. This finding is heartening given the increase in complexity and expertise necessary to collect data for multi-species indicators.

2.4 Chemical indicators of ecological condition

2.4.1 Introduction

Ecosystems, and the species within them, are dependent on both energy and matter. Energy by its' very nature can be only used or passed through a system, it can not be cycled in the traditional sense. Matter on the other hand is an ecosystems' basic building block and elements can be considered to be held in several different types of pools. Transformation or transportation of these inorganic nutrients can be by either biological or chemical processes and the cycles of four elements in particular (oxygen, carbon, nitrogen, and phosphorus) have great importance to life. Biogeochemical processes are fundamental to ecosystem organization and because they are at such basic level, alterations of these cycles can have profound effects across all species utilizing the ecosystem.

The use of biogeochemistry ecosystem indicators hinges on the theory that ecological systems are organized hierarchically (O'Neill et al., 1986, Allen, 1992). One of the more basic premises of this theory is that a relatively small set of principles can track complex systems that are organized at multiple levels. This premise allows for the development of indicators at the base or at key links of essential elemental processes because there exists a mechanism by which results can be translated up the hierarchical scale and indicate ecosystem health or change.

The cycling of carbon and oxygen are inexorably linked because these elements are often found combined in the form of carbon dioxide. The generation of oxygen is biological, but the cycling of carbon has both biological and geological aspects. The carbon cycle is a constant interaction between photosynthesis, where energy from the sun is used to produce carbohydrates and oxygen from carbon dioxide and water, and respiration, where carbohydrates and oxygen are used to produce energy, carbon dioxide, and water. Pools for carbon dioxide are ultimately oceans and rocks were geological process will also transform carbon. The nitrogen cycle is slightly more complicated because the main reservoir for nitrogen is the atmosphere and free nitrogen found there is inaccessible to living organisms. Additional complications arise due to the number of organisms which convert nitrogen to usable forms and the number of forms nitrogen can ultimately take. Although nitrogen is a basic constituent of amino acids and necessary for life, further complications within the nitrogen cycle arise because excess nitrogen can be harmful to plants and aquatic systems (NRC 2000c).

There are limits to how much nitrogen will stimulate plant growth and when these limits are reached, the ecosystem is termed "nitrogen saturated". In theory, excess nitrogen inputs are then transported out of the ecosystem by streams, groundwater, or the atmosphere. Alterations of the nitrogen cycle have had profound ecosystem effects such as contributing to acidification and increasing nutrient inputs to coastal ecosystems (Vitousek et al. 1997). National assessments of water quality show that excessive nutrients are the third highest source of impairments to waterbodies, accounting for almost 10% of the total (USEPA 2005c). Large alterations of these cycles can cause eutrophication, a process in which a nutrient enriched environment creates artificially high algae productivity and oxygen levels in the water are reduced (turn hypoxic) as these organisms die and decompose. The low oxygen content renders these waters uninhabitable. A dramatic example of eutrophication is the Gulf of Mexico's hypoxic zone which annually affects between 16-20,000 km^2, impacting fish and bottom-dwelling communities, and the economies that are supported by these species (Rabalais et al. 1999). Efforts to limit effects such as these have culminated in the addition of numerically based nutrient criteria to state and federal water quality standards (USEPA 1998c)

2.4.2 STAR Grants

Eleven Ecological Indicator grants used chemical indicators of ecological condition in some way. Six grants investigated nutrient dynamics as an indicator of ecological condition, three examined chemical indicators of anthropogenic disturbance and two examined the effects particular pollutants on ecosystem components (Table 5).

Table 5: Status and types of chemical indicator STAR Ecosystem Indicator Grants

Grant	Nutrient dynamics	Indicators of disturbance	Pollutant effects on ecosystem components	Ready for EPA review
R82-5685	X			
R82-5866		X		
R82-5868	X			
R82-6591	X			
R82-6592		X		
R82-6600		X		
R82-6601			X	
R82-6602			X	
R82-7637	X			X
R82-7641	X			
R82-7644	X			

Nutrient Dynamics

All six grants focusing on nutrient dynamics (Table 5) dealt in some way with nitrogen and the effects excess nitrogen may have on the ecosystem. These grants focused on nitrogen dynamics in freshwater systems (lakes), coastal zones (tropics and temperate zones), forests, and wetlands.

Two grants (R82-5868 and R82-6591) focused on bacteria assemblages and nutrient availability in freshwater systems. Both grants met with limited success in determining how nutrient supplies affect algae and bacteria (R82-5868) or zooplankton (R82-6591). Interestingly, these studies showed that lakes in Canada, New Hampshire, New York, Texas, and Vermont were not nutrient limited. Although nutrient concentrations suggested nutrient limitation, other conditions, such as the influence of fish predation on zooplankton, overwhelmed the potential effect that nutrient ratios may have had on the bacteria assemblages.

In contrast to the grants focusing on freshwater systems, the two Ecological Indicator grants (R82-7637 and R82-7644) that studied nutrient dynamics in the coastal zone showed potential for nutrient limitation. In one study (R82-7644), nutrient limitation occurred only when ammonium, which inhibits the uptake of nitrate by phytoplankton, reached a threshold level of 3 µM. The discovery of this threshold is a key finding, providing an unambiguous target for ecological condition monitoring and restoration.

Ecological Indicator grant R82-7637 developed a new bioindicator to assess nutrient supply in coastal waters. A series of elegant and complex field and laboratory experiments were conducted to determine how a long list of environmental conditions or variables affected macroalgae as bioindicators of nitrogen and phosphorus. Five species of macroalgae were compared and one (*Acanthophora spicifera*) proved to have excellent potential as an indicator of nutrient supply. The prospective bioindicator was tested over a wide geographic range (three sites in the Eastern Tropical Pacific, two sites in the Caribbean, and one site in Hawaii). Unfortunately, while this species is widely distributed in both tropical and subtropical habitats, it is not found in the temperate zone. In order to determine if macroalgae could be potential temperate zone bioindicators, four additional species of macroalgae were tested along the West Coast of the U.S. Species specific responses in the temperate zone experiments were not as clear-cut as the tropical experiments, however, the methodology was proved to be sound. Two different species of macroalgae were determined to have potential as bioindicators of nutrient supply for the southern California and Washington coastlines. The use of macroalgae as an indicator of nutrient supply dynamics of coastlines bridges the gap between immediate results obtained from water quality sampling programs and long-term results from ecological condition monitoring programs.

One grant (R82-5865) developed an indicator of tree leaf nitrogen based on remote sensing imagery in an attempt to model nitrogen cycles in potentially saturated forests. Field based measurements of tree leaf nitrogen correlated well with hyperspectral remote sensing imagery and these tight correlations allowed the researchers to produce a map of nitrogen concentrations across the entire study area within the White Mountain National Forest (New Hampshire and western Maine). This study was unsuccessful in providing a complete model of the entire nitrogen cycle, there was no direct link between tree leaf nitrogen levels and nitrogen concentrations in streams. While this study developed scientific groundwork for advanced monitoring and detection of forested areas at risk of nitrogen saturation, more work is needed to develop statistically significant relationships between leaf chemistry, remote sensing, and stream water quality.

Anthropogenic Disturbance

Three grants (R82-5866, R82-6592, and R82-6600) used chemical measures as indicators of anthropogenic disturbance. One grant (R82-5866) used stream pH as a component of a multimetric index of biological integrity. In the MAH, stream acidification, which can be caused by acidic deposition or coal mine drainage, is a stressor on the macroinvertebrate community. Two other grants (R82-6592 and R82-6600) investigated indicators of anthropogenic disturbance affects on key soil processes. Ecological Indicator grant R82-6592 developed a low cost indicator of soil health that was independent of soil type. This study developed an index of soil enzyme activity was that can consistently distinguish between agriculture and non-agriculture related soil practices. Ecological Indicator grant R82-7641 determined that total phosphorus in soil was the best variable for differentiating impacted and nonimpacted Florida wetland sites. It is notable that this relationship was validated with data from other, independent Florida and Georgia wetlands.

Pollutant Effects

Two Ecological Indicator grants (R82-6601 and R82-6602) focused on pollutants as indicators of ecological condition and in both cases found that easily and commonly measured regulated pollutant may have limited ecological relevance. This grant Ecological Indicator grant R82-6601 showed that ambient ozone concentrations (a common regulated measurement) are poor predictors of ozone damage to forested regions of California. This discrepancy is due to physiological inactivity of trees during the season in which there are high ozone concentrations. Water transportation processes directly affect how much ozone is taken up by a plant and this grant developed a better model to mimic water transportation within trees and out of plant leaves (stomatal conductance). The resultant model coupled ozone exposure, forest physiological activity, and soil moisture content. The use of stable carbon isotopes as a possible indicator of tree water transportation processes was investigated. Results showed that stable carbon isotopes highly predict mean daily conductance at 30 day intervals, but results showed significant site variation indicating the need for more research if regionally applicable indicator of potential for ozone damage is desired.

Ecological Indicator grant R82-6602 found that PM_{10} (a measure of the average amount of airborne particulate matter $\leq$ 10 microns in size) is a good indicator of soil metal contamination, all eight metals tested for in soil samples were significantly correlated with mean annual PM_{10}. In addition, dandelion (*Taraxacum officinale*) leaf tissue concentrations of four metals (chromium, manganese, lead, and zinc) were associated with soil contamination. However, the results of this study indicated that the concentration of metals in soil at a site does not predict the amount taken up by plants, and that other factors such as season, dandelion genetics, or site conditions influence dandelion uptake of metals. Taken in total, findings from this grant suggest that dandelions may not be a particularly effective bioindicator for quantifying metal contamination.

Indicators ready for EPA Review

The width and breadth of scientific experimentation of Ecological Indicator grant R82-7637 has shown that many of potential confounding factors of a bioindicator of coastal nitrogen supply can be controlled. Since much of the grant funds went to testing a scientifically sound experimental design, the results from this grant are conclusive enough that a formal EPA testing and review should be straightforward and simple. There is enormous utility for an ecological indicator which can bridge the time gap between instantaneous samples of water quality sampling and long-term monitoring. The macroalgae indicator proposed by this grant can potentially be this indicator and thus warrants further testing and development.

2.4.3 Summary

In conclusion, the STAR Ecological Indicator grants investigating chemical indicators of ecological condition have made progress similar to the other STAR categories. As a body of research, the chemical indicator grants have primarily focused on nutrient dynamics, nutrient dynamics, and pollutant uptake by plants. Several potential indicators were identified and in one case, research has progressed to the stage where a new ecological indicator is ready to be rigorously evaluated (R82-7637).

2.5 Remote sensing techniques to develop landscape indicators

2.5.1 Introduction

Remote sensing can be defined simply as the analysis of data collected by instruments not in physical contact with the objects of interest (Avery and Berlin, 1992). With respect to ecological indicators using remote sensing, this involves the search for patterns within the imagery obtained from aircraft or satellites and relating this to patterns observed in field collected data. For the majority of users, remote sensing measures the electromagnetic spectrum passively as reflections off of surfaces, but recent advances in sensor technology have allowed active sensors (e.g. RADAR and LIDAR) to be used in areas where passive sensors do not perform optimally. Analog systems (film from cameras interpreted manually by analysts) have historically dominated the industry due to their low cost and high resolution but are slowly being replaced by digital systems (Mondello et al., 2004). The launch of satellite the Landsat-1 in 1972 (deactivated in 1978) heralded the beginning an era of civilian digital remote sensing in which the electromagnetic spectrum has been split into increasingly smaller segments (bands) with increasing higher spatial resolution, covering increasingly larger areas of the earth (swath).

Landsat-1 was part of the first generation of space-born imagers and carried a multi-spectral scanner which yielded four digital numbers per digital picture element (pixel). The four digital numbers corresponded to the reflection measured in the visible and near-infrared wavelengths and the ground resolved distance (GSD) of each pixel was a square with 80m sides. Technological advances have now produced space-born imagers with a pixel resolution of 6 inches (which are comparable to traditional aerial photography) and aerial hyperspectral imagers can now yield hundreds of digital numbers per pixel that are far in advance of any analog system. Landsat-5 was launched in 1984, is still in service and carries a sensor which has 7 bands (6 with 30m GSD, 1 with 120m GSD). The Landsat program was commercialized in 1985 which in effect placed data collected by Landsat-5 out of the reach of many researchers and government agencies (NRC 1997b).

In response to the privatization program, the Multi-Resolution Land Characteristics (MRLC) Consortium was formed in 1993 by six federal agencies to purchase mid-1990's Landsat-5 imagery for the conterminous U.S. and to develop a land cover dataset called the National Land Cover Dataset (Volgelmann et al., 2001). The NLCD updated the only other existing land use and land cover data set for the U.S. which was developed in the 1970s (USGS 1990). The classification scheme of the NLCD included 21 thematic categories, however, accuracy, even at the course seven category Anderson Level 1 Classification (water, urban, barren, forest, shrub, agricultural, and wetlands) is considered relatively low and averaged only 80.1% across the 10 federal regions (Volgelmann et al., 2001). Landsat-7 was launched in 1999 (Landsat-6 failed to achieve orbit) and has 8 bands (1 with 15m GSD, 6 with 30m GSD, and one with 60m GSD) and a second-generation MRLC consortium of nine federal agencies was formed to purchase 2001 Landsat-7 imagery for the entire United States to update the NLCD.

2.5.2 STAR Grants

Twelve Ecological Indicator grants used remote sensing techniques in developing landscape indicators that quantify and characterize the geographic extent of key ecosystem attributes. Remote sensing is commonly used to delineate land use patterns, and eight employed some variation of this methodology. Only four grants used remote sensing technologies to develop new ecological indicators.

Land Use / Land Cover

The nine grants (R82-5866, R82-5867, R82-5870, R82-5871, R82-6591, R82-6597, R82-6600, R82-7638, and R82-7642) that used remote sensing to depict land cover and land use did so at a very low thematic level (e.g. percent forest) and used either manual interpretation of aerial photography or coarse scale digital imagery. The use of remote sensing in this way is more truly a method for creating metrics of ecosystem extent or status (NRC 2000b) than a true indicator of ecological condition. As such, for the most part, many of these grants used remote sensing products to produce one, or several, metrics that could potentially be correlated with the ecological attribute of interest. Most grants that used remote sensing technologies were consumers of products produced by other researchers, such as those using the NLCD, but some used raw data from Landsat-5 or other sensors. Aerial photography was the most commonly used data source to supplement or modify land use data from the NLCD and was often used as a source of historical land cover information.

Percent forest was the metric most commonly calculated using remote sensing; however, a general consensus did not emerge with respect to the question of whether land cover can act as an indicator of ecosystem stress. In some studies, current land use was one of several potential indicators, and in others only historical land use was identified as a possible indicator. Landscape metrics (e.g. fragmentation, patch size/shape) are easily calculated using GIS algorithms but no consistent patterns of ecological influence could be detected across studies. While land use/land cover information has been predicted to be an important component of ecosystem stress, the lack of consistent support for this hypothesis across these eight grants points to the need for continued research before land cover indicators can be formally tested. The lone exception is R82-5871 whose results imply that the percent impervious surfaces of a watershed could be a suitable indicator of both biological integrity as measured by fish, and stream condition as measured by instream geography.

Remote Sensing large areas

Two Ecological Indicator grants (R82-6598 and R82-7638) used remote sensing technologies to "scale-up" existing ecological indicators. Ecological Indicator grant R82-6598 used both passive (e.g. Landsat) and active (RADAR) sensors in developing several significant relationships between remote sensing variables and forest structure. These relationships are particularly exciting because of the well known relationship between forest bird species and vertical complexity (MacArthur and MacArthur 1961). RADAR, in combination with Landsat imagery, proved to be a useful in measuring canopy height and basal area. The development of a measurement technique such as this makes it feasible to map forest structure continuously over large areas, which in turn would allow for cost effective assessment of bird habitat over the same large areas. This Ecological Indicator grant also investigated the feasibility of mapping understory vegetation with passive sensors and found that the readily available Landsat imagery is more effective for this task than more expensive hyperspectral sensors.

Hyperspectral remote sensing imagery were also evaluated by Ecological Indicator grant R82-7638 in an attempt to quickly scale up field based indicators of stream condition. Stream depth was determined to be the stream characteristic that is most detectable from the reflectance data. This is a significant finding because this is one of the first studies to separate the signal received from the water column from the substrate, a difficult situation as water absorbs certain wavelengths of light. This study is part of a growing body of literature that is showing it is possible to study fluvial systems with hyperspectral imagery.

New Indicators

Finally, two Ecological Indicator grants (R82-6112, R82-5865) attempted the much more difficult task of developing new indicators using remote sensing technologies. Ecological Indicator grant R82-6112 used a multi-temporal approach to identify indicators of landscape degradation by grazing in the arid Southwest. This grant used the entire 27 year (1972-1998) archive of Landsat imagery and attempted to test a full suite of indicators by investigating four metrics: Soil Adjusted Vegetation Index (SAVI), a measurement of vegetation greenness developed for arid environments; Soil Stability Index (SSI), a measurement of soil erosiveness; landscape patterns, measures of fragmentation; and piosphere generation, a measure of the grazing gradient radiating from a water point. All of these indicators showed some promise. Effects on rangelands caused by cyclical events, such as the El Niño-Southern Oscillation, were detected using the SAVI, and the SSI was significantly related to both water availability and grazing. The development of a tool for aiding in the identification of grazing gradients would greatly enhance future research efforts.

As previously discussed, R82-5865 showed that it is possible to use airborne hyperspectral remote sensing sensors to determine leaf nitrogen concentration of forests. Canopy level nitrogen concentration is in turn an accurate predictor of aboveground forest productivity. Although the ultimate goal of the study, predicting the amount of nitrogen leaving the system via streams using remotely sensed data, was not accomplished, the characterization of these two relationships is an important step forward in linking terrestrial carbon and nitrogen cycles. Tentative relationships were found between remotely sensed data of individual tree species and nitrate in streams but additional research is necessary for full understanding.

2.5.3 Summary

In conclusion, it is clear that there is strong interest in the scientific community in employing remote sensing technologies to quantify and characterize the geographic extent of key ecosystem attributes. The appeal is basic, as research progresses it may be possible to rapidly scan from the air or space key ecosystem characteristics that will provide information regarding the health and status of biological systems. The recent advent of digital processing of remote sensing imagery has speeded this process, however, much research remains. Some STAR Ecological Indicator grants have made significant progress towards developing targeted indicators (R82-5865 and R82-7638) but in general the use of use land use and land cover as an indicator remains elusive. Mixed results in the grant studies showed that land use and land cover is a powerful indicator in some systems, while not useful in others.

3.0 CONCLUSIONS

A comprehensive assessment of the 28 Ecological Indicator grants funded by the EPA STAR Ecological Indicator program has shown significant progress towards EPA's goal of designing effective indicators, monitoring systems, and for measuring the exposure of ecosystems to multiple stressors at local, regional and national scales. The majority of the $18.5M worth of Ecological Indicator grant funding has gone to further long term gains in environmental science and have produced an impressive array of new analytical methods, new tools, peer-reviewed publications and presentations to the public (Appendix A). These results are already in use by federal, state, local and tribal agencies and a variety of non-government user groups (see deliverable 1 of this contract – Compendium Reports of 1997, 1998, and 1999 Ecosystem Indicator Grants).

Many of the STAR Ecological Indicator grants have focused on basic research and it is not appropriate, and in some cases destructive, to measure success based on short-term relevance (COSEPUP 1999). Two additional complications arise during attempts to measure the success of the STAR Ecological Indicator grants. First, a consensus has not emerged with respect to suitable metrics for measuring success of basic science research, especially with respect to GPRA (COSEPUP 1999, Van Houten 2000), and secondly, not enough time has elapsed since the 1997-99 Ecological Indicator grants have been completed in order to assess their impact (GAO 2000, NRC 2003). The EPA STAR program has undergone nine formal reviews (NRC 2003) since its inception in 1995 and this document was not designed to measure the impact of the EPA STAR grants and thus should not be considered with the same light as these reports. This document presents to EPA a synthesis of the results of the STAR Ecological Indicator grants and what are some very exciting developments in ecological indicators research.

Contributions by the STAR Ecological Indicator program towards advancement of indicator research are undeniable. Even though the STAR Ecological Indicator program was not designed to shepherd a new indicator through the entire process outlined by Jackson et al. (2000), this body of supported research has produced indicators with extremely high potential and applicability and some have already risen to this level or are extremely close to doing so. Three potential indicators offer high potential and intriguing possibilities (R82-5865, R82-6598, and R82-6602); two indicators have issues that should be resolved with additional research before formal evaluation can proceed (R82-5871 and R82-7644); two indicators are ready for formal evaluation (R82-7637, and R82-7639); and one indicator has undergone a self review using formal evaluation procedures (R82-5869). The fact that eight of the 28 grants have products so far along in this investigative process is proof of EPA's return on investment.

High Potential Indicators

Three grants have identified potential ecological indicators that offer enough promise that they should be targeted for additional EPA research to evaluate their utility. One grant developed an indicator of foliar nitrogen using hyperspectral remote sensing technologies (R82-5865), another developed an indicator of forest structure using RADAR (R82-6598), and a final grant developed an indicator of soil metals contamination (R82-6602) based on routinely monitored particulates (PM_{10}). These grants all found strong correlations between the indicator and the ecological condition response variable. The correlations found are of sufficient strength and usefulness to EPA constituents to warrant additional investment of EPA resources to determine if the relationships hold true in other systems.

Additional Research Required

Two grants (R82-5871 and R82-7644) have developed ecological indicators that have show an extremely high potential for significant returns, and further research is needed to prove the utility of each. One indicator (R82-5871) has shown strong correlations between the amount of impervious surfaces in a watershed and two different measures of biological integrity. This research is part of a growing body of evidence that conclusively shows human impacts on ecological condition. Results of this entire body of research have been summarized by others (CWP 2003) and lingering controversy and scientific research remains. Sufficient support for (Arnold and Gibbons 1996, Heinz Center 2002, and USEPA 2002) and criticism of (USEPA SAB 1999) the use of impervious surfaces as an indicator of watershed health and biological integrity exists and these issues must be resolved before evaluation or widespread implementation of such an indicator.

Another grant (R82-7644**)** identified a possible threshold of nutrient limitation in an estuarine system that could be a useful indicator. Ammonium inhibits the uptake of nitrate and, theoretically, a threshold could be developed that could be used to identify causes of harmful algal blooms in a variety of estuarine systems. Additional research into this ammonium threshold should be integrated into the EPA STAR program for the Ecology and Oceanography of Harmful Algal Blooms (USEPA 2000b) and other coordinated federal research into harmful algal blooms causes and effects that is underway (GAO 1999, NTSC 2000).

Indicators Ready for Review

The three ecological indicators closest to implementation are all water quality indicators. Two of these (R82-7637, and R82-7639) having undergone extensive testing and experimentation, but further tests and formal review should be performed prior to widespread adoption. One indicator (R82-7639) is designed to determine the sources of fecal contamination in water using genetic techniques. Interest in this indicator is expected to be high, since nationwide, pathogens are second most common cause of impairments to U.S. waters and currently affect 13% of waters reported on EPA's 2002 303(d) list (USEPA 2005c). This indicator relies on state-of-the-art DNA techniques that are still in development and issues related to conflicting results have arisen from methodological differences in application of this technique (Field et al., 2003). Review within formal EPA evaluation guidelines will provide a convenient framework to determine differences of these analytic techniques and should be resolved prior to widespread implementation.

A second indicator ready for formal EPA review (R82-7637) deals with nutrients in coastal systems. While oceans are not tracked by the EPA's 303(d) list, coastlines, estuaries and bays are. Nutrient enrichment of these systems is a growing problem, especially in the historically nutrient poor waters supporting coral reefs. This indicator has been designed to track nutrient dynamics in estuaries, bays, and coastal waters using three different widespread species of macroalgae. A series of elegant experiments were used to develop this indicator, which has now been tested over a wide geographic area. A serious drawback of this indicator is that local calibration may be necessary prior to widespread use. While this monitoring technique is ready to be applied in most temperate and tropical coastal systems, it should be formally evaluated using EPA guidelines prior to extensive adoption.

A final indicator (R82-5869 – FORAM Index) has been evaluated by the principal investigators within the context of EPA guidelines (Jackson et al., 2000). The FORAM index is well developed, is one of only a handful of successful indicators of coral reef habitat potential, and is perhaps the only such indicator that is independent of coral populations. The FORAM Index has been tested at four sites worldwide and has wide regional applicability. This index can determine if decline in coral dominance on a reef is due to nutrification or episodic stress events, such as temperature extremes or hurricanes. A fascinating aspect of this biological indicator lies in its ability to be applied to reef sediments, extending the analysis time scale backwards several decades.

Through its STAR Ecological Indicator Program, EPA has invested over $18.5M of extramural support towards its ultimate goal of developing indicators of ecosystem stress. This significant infusion of research funding has already paid off in the terms of contributions to basic research, identification of a variety of potential indicators, and the production of new ecological indicators. Placed within the context of other federal efforts to determine cause and affect relationships between ecosystem responses and anthropogenic stressors, EPA is making significant strides towards developing a system of national level indicators of ecosystem health.

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APPENDIX A – PRODUCTS

Grant	Principal Investigator	Title	Funding	New Methods	Peer-Reviewed Articles	Presentations	Tools, Models, GIS
R82-5865	John Aber	Foliar Chemistry as an Indicator of Forest Ecosystem Status, Primary Production and Stream Water Chemistry	$ 850,000		3	11	1
R82-5866	Robert P. Brooks	Using Bioindicators to Develop a Calibrated Index of Ecological Integrity for a Forested Headwater Ecosystem	$ 995,000		1	26	
R82-5867	Val Beasley	Environmental Factors That Influence Amphibian Community Structure and Health as Indicators of Ecosystem Integrity	$ 1,299,991		3	36	1
R82-5868	James Grover	Microbial Indicators of Biological Integrity and Nutrient Stress for Aquatic Systems	$ 748,787		5	17	
R82-5869	Pamela H. Muller	Foraminifera as Ecosystem Indicators: Phase 1- A Marine Benthic Perturbation Index; Phase 2- Bioassay Protocols	$ 344,545	1	11	30	1
R82-5870	Carl Richards	The Development and Evaluation of Multi scale Mechanistic Indicators of Regional Landscapes	$ 925,000		1	23	1
R82-5871	Anne Spacie	Development and Evaluation of Ecosystem Indicators for Urbanizing Midwestern Watersheds	$ 672,323		12	13	2
R82-6112	Neil West	Characterization of the Ecological Integrity of Commercially Graded Rangelands Using Remote Sensing-based Indicators	$ 340,617		3	12	3
R82-6591	Richard S. Stemberger	An Integrative Aquatic System Indicator	$ 888,661		2	6	1
R82-6592	Richard P. Dick	Soil enzyme stability as an ecological indicator	$ 196,806		1	7	
R82-6593	Michael C. Newman	Are genetic diversity and genetic differentiation bioindicators of contaminant impact on natural populations? Fundulus heterclitus as a model of estuarine species	$ 727,255		3	8	
R82-6595	Stephen Threlkeld	Effects of interacting stressors in agricultural ecosystems :Mesocosm and field evaluation of multilevel indicators of wetland responses	$ 897,634				
R82-6596	Helen Michaels	Demographic and genetic factors affecting population viability of Lupinus perennis, as an indicator species of oak savanna	$ 289,178	2		24	
R82-6597	David S. Leigh	Land use and geomorphic indicators of biotic integrity in piedmont streams	$ 780,834		4	33	1
R82-6598	Steven W. Seagle	Development and testing of a multi-resource landscape-scale ecological indicator:forest fragmentation, structure, and distribution relative to topography	$ 856,598		3	23	1

Grant	Principal Investigator	Title	Funding	New Methods	Peer-Reviewed Articles	Presentations	Tools, Models,GIS
R82-6599	Dan E. Krane	Intraspecies Genetic Diversity Measures of Environmental Impacts	$ 420,278		6	17	
R82-6600	Monica G. Turner	Ecological indicators for large river-floodplain landscapes	$ 667,351	1	10	35	1
R82-6601	Allen H. Goldstein	Modeling ozone flux to forests across an ozone concentration gradient in the Sierra Nevada Mts, CA	$ 621,367	1	13	13	1
R82-6602	Steven H. Rogstad	Ecosystem monitoring via genetic diversity surveys of dandelions using VNTR multilocus DNA probes,	$ 291,045		21	25	
R82-6603	Susan L. Anderson	Genetic diversity in California native fish exposed to pesticides	$ 649,003		4	24	
R82-7637	Peggy Fong	Developing an Indicator for Nutrient Supply in Tropical and Temperate Estuaries, Bays and Coastal Waters Using the Tissue Nitrogen and Phosphorus Content of Macroalgae	$ 399,335		17	18	
R82-7638	Duncan T. Patten	Developing Effective Ecological Indicators for Watershed Analysis	$ 868,242		10	20	1
R82-7639	Katharine G. Field	Molecular Detection of Anaerobic Bacteria as Indicator Species for Fecal Pollution in Water	$ 223,829	2	7	20	
R82-7640	Robert P. Brooks	Stream Plethodontid Assemblage Response (SPAR) Index: Development, Application and Verification in the MAHA	$ 397,304			3	1
R82-7641	K.R. Reddy	Biogeochemical Indicators of Watershed Integrity and Wetland Eutrophication	$ 639,410		7	13	1
R82-7642	Lucinda Johnson	Effects of Forest Fragmentation on Community Structure and Metapopulation Dynamics of Amphibians	$ 769,624		1	8	1
R82-7643	James T. Oris	Multi level Indicators of Ecosystem Integrity in Alpine Lakes of the Sierra Nevada	$ 894,627			13	
R82-7644	Richard C. Dugdale	Integrative Indicators of Ecosystem Condition and Stress Across Multiple Trophic Levels in the San Francisco Estuary	$ 881,062		5	40	

APPENDIX B – COMMON THEMES

Grant	Study System	Focus of Study	Focus of Study	Focus of Study	Primary Stressor	Water Quality	**Genetics**
R82-5865	Forest	Forest			Nutrients	Y	
R82-5866	Forest	Birds	Macroinvertebrates		Anthropogenic disturbance		
R82-5867	Wetlands	Amphibians			Anthropogenic disturbance	Y	
R82-5868	Freshwater	Zooplankton	Bacteria		Nutrients	Y	
R82-5869	Marine	Protists				Y	
R82-5870	Forest	Landscape			Anthropogenic disturbance	Y	
R82-5871	Forest	Macroinvertebrates	Fish	Freshwater mussels	Anthropogenic disturbance	Y	
R82-6112	Grassland	Landscape			Grazing		
R82-6591	Freshwater	Zooplankton			Nutrients	Y	
R82-6592	Forest	Soil			Anthropogenic disturbance		
R82-6593	Marine	Fish			Pollutants	Y	Y
R82-6595							
R82-6596	Woodland	Plants			Anthropogenic disturbance		Y
R82-6597	Freshwater	Macroinvertebrates	Fish		Anthropogenic disturbance	Y	
R82-6598	Forest	Forest	Birds				
R82-6599	Freshwater	Fish	Insects		Pollutants	Y	Y
R82-6600	Forest	Birds	Soil	Forest	Anthropogenic disturbance		
R82-6601	Forest	Plants			Pollutants		
R82-6602		Plants	Soil		Pollutants		Y

Grant	Study System	Focus of Study	Focus of Study	Focus of Study	Primary Stressor	Water Quality	Genetics
R82-6603	Freshwater	Fish			Pollutants	Y	Y
R82-7637	Marine	Macroalgae			Nutrients	Y	
R82-7638	Freshwater	Forest	Macroinvertebrates		Anthropogenic disturbance	Y	
R82-7639	Freshwater/Marine	bacteria			Nutrients	Y	Y
R82-7640	Freshwater	Amphibians			Anthropogenic disturbance	Y	
R82-7641	Wetlands	Soil			Nutrients		Y
R82-7642	Wetlands	Amphibians	Macroinvertebrates		Anthropogenic disturbance		
R82-7643	Freshwater	Macroinvertebrates	Zooplankton	Fish	Nutrients	Y	Y
R82-7644	Marine	Macroinvertebrates	Zooplankton	Fish	Nutrients	Y	Y

APPENDIX C – GEOGRAPHIC DISTRIBUTION