External Review of the Marine Microbiology Initiative (MMI)

MMI Portfolio Review

Report from the AAAS External Advisory Committee

September, 2012

Conducted by the American Association for the Advancement of Science (AAAS) Research Competitiveness Program

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Table of Contents

Executive Summary

This report provides the findings and recommendations of the AAAS External Advisory Committee (EAC), which was tasked with conducting a review of the Marine Microbiology Initiative and proposing recommendations for Phase II (2010-15) implementation based on the program's Phase I (2004 -10) outcomes. To address the requirements in the MMI Evaluation RFP, the AAAS review conducted its review over the course of one year.

First, assessment of the scientific outcomes of 70 Phase I grants, including CAMERA, GBMF Investigator awards, and the contributions of MMI to the field of marine microbiology, was carried out by four independent review panels. A total of 18 expert reviewers participated in the four panels. Each independent review panel was chaired by an EAC member in order to provide perspective and continuity across the separate review panels. Second, in order to understand the processes used by MMI to select and evaluate research that aligned with MMI goals, AAAS staff and the EAC Chair interviewed current and former MMI staff and GBMF scientific advisory board members. A survey of MMI grantees was also conducted to understand these processes and the impacts of MMI from the grantee point of view. Third, through a subcontract, a bibliometrics and social network assessment was done to understand the quantitative impact of the MMI grantees in the overall field of marine microbiology. The EAC was engaged through the entire process providing input and advice to AAAS staff throughout the study and convening monthly with AAAS to discuss project updates. Finally, all of these data were reviewed by the EAC during a two day in-person meeting in July in order to develop their findings and overarching recommendations. During its deliberations, the EAC was consistently unanimous and this report represents those views.

The MMI set out to transform the efforts in marine microbiology into a new field of microbial ecology in ten years - an extremely difficult goal in the strictest sense. Realistically, no single entity could be expected to achieve such an ambitious objective in this timeframe. But the program did transform significant aspects of marine microbiology that may ultimately help to transform the field. **The choice of marine microbiology as a field for major investment in 2003 proved a very wise investment by GBMF and there is little doubt that the program significantly accelerated the rate of progress on some of the major questions in the field.** Moreover, the established leaders chosen to lead major programs all clearly performed very well**.**

The most transformative aspect of MMI was bringing "omics" techniques (genomics, metagenomics, metatranscriptomics) to the forefront of marine microbial ecology and to support major breakthroughs in microbial observation. GBMF Investigators clearly demonstrated the capabilities of metagenomic approaches for studying marine microbes. Before the MMI, many were skeptical that these approaches could successfully advance and refine knowledge of the marine microbes. **The pioneering work of the MMI grantees transformed methodologies and approaches deemed high-risk only 8 years ago to relatively tractable and appropriate tools for projects with similar scope and resources. The value of these approaches is now part of the canon of marine microbiology.** Through these efforts, the MMI significantly raised the profile and importance of marine microbiology.

The major scientific impacts to the field of marine microbiology from the MMI include:

- Significant advances in our capacity to identify and observe microbes in their ocean environment, including remote, subsurface locations.

- Major insights into the role of microbial communities in cycling of major nutrients, including nitrogen, sulfur, and carbon.
- New tools and strategies to understand gene expression in marine microbes and how that expression influences major ocean biogeochemical processes.

MMI invested heavily in equipment infrastructure to ensure that scientists could work with cutting edge, highest quality facilities. That strategy worked quite well, with genomics investments showing significant early returns and others showing great promise. The ability of MMI to respond quickly to technology changes and take higher risks than traditional funding agencies, significantly helped to bring advanced, diverse technologies to study the marine microbial world. **New tools developed by MMI may well represent one of the most significant and enduring legacies of the program. Thus, the EAC recommends that to continue leading-edge research for Phase II, MMI should maintain and upgrade this cutting-edge equipment as technologies rapidly develop. Planning for the long-term sustainability of these facilities must also guide legacy planning as MMI winds down.**

The vision for CAMERA, the largest MMI-supported facility, was to create a central data repository along with bioinformatics tools to serve the needs of the marine microbiology community and other users. Several questions should be answered to determine the future of CAMERA in Phase II. The first is whether CAMERA can adequately meet the needs of a critical mass of users in the marine microbiology field with available GBMF resources, while simultaneously remaining on the cutting-edge and facilitating the next phase of marine microbiology research. Second, it is critical that future plans for CAMERA include a sustainable business model. Finally, next-generation DNA sequencers have moved sequencing away from large genome centers and into the laboratories of individual investigators. By providing next generation sequencers, MMI facilitated evaluation of these new technologies in the context of metagenomics studies. This was a strategy the EAC viewed very positively because it created great flexibility to address priority research questions as they emerged while facilitating the training of students and post-doctoral fellows in large-scale sequencing. Given this change, the EAC believes there is value in further developing the capability for data analysis at local levels by experts in specific areas of research, as an adjunct activity to a more centralized database model exemplified by CAMERA.

Given these considerations, the EAC does not recommend continuing CAMERA in its present form. One option is to evolve CAMERA into a Data Coordination Center to assist scientists in submitting data for long-term storage in accordance with the expectation of the MMI program staff, in finding and linking all types of data related to marine microbiology, and in ensuring data quality and reliability. The Data Coordination Center could also collaborate with other Federal and Foundation-funded projects regarding database development and management. This strategy would be an extremely valuable contribution to the field as the size and types of datasets continue to increase.

With regard to program design and implementation, Phase I had the very broad vision "to transform the field of marine microbiology" but the goals and timelines that were not clearly understandable. The EAC panel notes, however, significant progress in identifying realistic and attainable stretch goals for Phase II of the program.

The process for choosing GBMF Investigators in Phase I, although highly successful for supporting leading researchers in marine microbiology and producing publications in top tier journals, was not transparent to either the research community or the AAAS review panels. In Phase II, MMI asked the community to submit ideas, followed by invitations to submit proposals. The challenge, of course, is to match individual proposal outcome goals with the MMI 2015 and 2019 time-phased outcomes without becoming too prescriptive and thus too risk adverse.

The EAC also found uneven reporting on grants, making it difficult to assess the impact of MMI funding beyond publications, although the committee had a sense that the impact of the program was probably much greater than reported. **The reports also created an impression of many strong and loosely interlinked projects rather than a unified and integrated program. As the program moves forward, MMI staff should help coordinate and assist in networking the individual Phase II proposal grantees so that they align as a group with the new long term 2019 time-phased outcomes, given that these targets are quite specific.**

The perception by the marine microbiology community of the MMI is a very important consequence of the GBMF funding a large percentage of the marine microbiology field. To be seen as a thoughtful contribution, the broader marine microbiology community needs to understand the decision-making processes utilized for award selection, and how these decisions track with the program's long-term, targeted time-phased outcomes. **The EAC, therefore recommends that the GBMF find ways to bring the marine microbial research community into their advisory process. One approach would be to create an MMI Science Advisory Committee comprising experts that report directly to the MMI program staff. This group would be helpful in identifying researchers from other areas such as biogeochemistry and nutrient dynamics whose engagement will be important for MMI to reach its 2015 and 2019 time-phased outcomes (microbial interaction and nutrient flow).**

While Phase I had notable successes, many opportunities remain. Perhaps the most striking remaining need in a program that seeks to transform the field to microbial ecology is a more inclusive and comprehensive examination of how key **microbial groups interact with a wide range of other organisms**, from many other microbes, through grazers and up through the food web. To date, the program has largely ignored interaction with higher organisms. Similarly, the noteworthy efforts within MMI to consider viruses could be extended to consider viral impacts on microbial (and thus nutrient) dynamics. The goal of achieving a "transformed field" hinges on strengthening the "ecology" component of the program, which can currently claim some clear victories, but also many significant gaps. Noting the positive reception that the DARWIN modeling received by the AAAS review panel, the use of models could be expanded and additional measurements added to expand the current program. One other opportunity that could substantially raise the profile of the program would be a focus on changing oceans and the relative impacts of human and natural perturbations.

Though the MMI cannot encompass all aspects of marine microbial ecology, it should prioritize which remaining opportunities are essential to attaining Phase II goals and define a strategy to address those opportunities in the remaining lifetime of the MMI. The program may wish to consider how to expand its work to address coastal environments, deeper waters or sediments – all of these environments contribute to microbial regulation of nutrient cycling in the world's oceans.

Finally, legacy strategies should be a priority focus at this time. Despite some clear successes, the scope of the MMI program and its legacy could be significantly enhanced to become "transformative". If GBMF and MMI decide they want the program impact to extend beyond marine microbial ecology community, a framework and detailed work plan should be developed to ensure that this occurs. The first question to ask is “which audiences need to be aware of the transformation?” Once this basic question has been answered, MMI can develop a strategy. In short, a carefully considered, well-resourced synthesis plan with clear targets requires several years of commitment and effort, and must begin well in advance of the end of the program.

Thus the EAC observes that **if there is hope for succession through other funding mechanisms after the MMI, a specific succession plan should be developed before MMI funding is completed and participating scientists retreat to other interests. This plan should identify research leaders willing to spearhead any follow-on initiatives as well as detailed plans for how such a program might be funded.**

In addition to maximizing the impact of the program, MMI should develop a synthesis plan and identify the MMI grantees who will play a leadership role in the implementation of that plan. That effort requires that MMI define their target audience and then develop a well-defined and specific roadmap to ensure that MMI discoveries and conclusions reach the desired audience(s). Ideally that synthesis plan should consider which metrics can be monitored to assess impacts and success with the target audiences.

Introduction

Report Overview

At the request of the Gordon and Betty Moore Foundation (GBMF), the AAAS conducted an independent review of Phase I of the Marine Microbiology Initiative (MMI): a 10-year, $145 million effort to answer fundamental questions about the immense diversity of marine microorganisms and their role in ocean health. During this period (2004-10), the MMI granted approximately 70 awards supporting individual researchers, development of methods, and formation of community resources. An external review was undertaken on the first three years of the program in 2007. The current report builds on that report and provides the findings and recommendations of the AAAS External Advisory Committee (EAC), which was tasked to conduct a review of the MMI portfolio and to draw recommendations on future planning based on the program's Phase I outcomes. The EAC members are listed below (bios included in Appendix I):

- Gary Borisy, President and Director of the Marine Biological Laboratory
- Claire M. Fraser-Liggett, Director of the Institute for Genome Sciences; Professor of Medicine, University of Maryland School of Medicine, Baltimore
- Robert B. Gagosian (**Chair, EAC**), President/CEO of the Consortium for Ocean Leadership
- Margaret Leinen, Associate Provost of Marine and Environmental Initiatives and Executive Director of the Harbor Branch Oceanographic Institute, Florida Atlantic University
- Paul Snelgrove, Canada Research Chair in Boreal and Cold Ocean Systems; Professor, Ocean Sciences Centre and Biology Department, Memorial University

In response to the charge from the MMI Evaluation RFP, the AAAS review included the following:

- review of scientific and technical outcomes from Phase I grants
- review of processes used by MMI to select and evaluate research that aligned with MMI goals
- in-depth review of the CAMERA project
- in-depth review of the GBMF Investigator awardees
- survey of all MMI grantees
- bibliometric and social network mapping on MMI grantees
- analysis of the contributions of MMI grantees to the field of marine microbiology
- provide recommendations on Phase II direction and strategies

To address these requirements, AAAS conducted a comprehensive review over the course of one year commencing in September 2011 (overview of the process is provided in Appendix II). First, an assessment of the scientific outcomes of Phase I grants, including CAMERA, GBMF Investigator awards, and contributions of MMI to the field of marine microbiology, was carried out by four independent review panels. The expertise of each review panel was tailored to the research areas under review. 18 expert reviewers participated in these panels (see Appendix III, for reviewer names and affiliations), with each panel chaired by an EAC member in order to provide perspective and continuity across the separate review panels. Second, in order to understand the processes used by MMI to select and evaluate research that aligned with MMI goals, AAAS staff and the EAC Chair interviewed current and former MMI staff and GBMF scientific advisory board members. A survey of MMI grantees was also conducted to understand these processes and the impacts of MMI from the grantee point of view (Appendix IV). Third, through a subcontract agreement with Science Metrix Corp, a bibliometrics and social network assessment was done in order to understand the quantitative impact of the MMI grantees relative to the overall field of marine microbiology. And finally, all of these data were reviewed by the EAC and synthesized in order to develop their findings and overarching recommendations. To prepare this report, the EAC met in-person over two days in July to discuss the MMI program goals, program implementation and funding approaches, and scientific outcomes. The meeting agenda is provided as Appendix V. The committee also reflected on the broader impacts of the MMI on the marine microbiology research community. The EAC provided input and advice to AAAS staff throughout the entire study and convened monthly with AAAS to discuss project updates.

This report focuses on MMI successes in the context of the previous state of the field of marine microbiology, research highlights, commentary on CAMERA, discussion of MMI management, as well as a brief description of remaining opportunities and comments on the legacy of MMI.

State of the Field Pre-MMI

At the onset of the MMI in 2003, the field of microbial ecology faced significant challenges and considerable opportunities. Although marine microbes were widely recognized as key players in nutrient cycles and other major processes, the field lacked the capacity to address even the most basic ecological questions: Which organisms are there? What do they do? How do they interact? Multiple barriers had stymied marine microbial research since studies began more than 75 years ago. The inability to grow most microbes in culture, in tandem with limited morphological characteristics capable of differentiating species, created a major taxonomic impediment that resulted in treatment of microbes as a “black box” with little knowledge of the role of each species. Little was known of the synoptic distribution of most marine microbe groups. While satellite imaging revolutionized our ability to observe pigmented microbes (e.g., phytoplankton) living close to the ocean’s surface, satellite technology cannot penetrate into deeper layers, provide information on most non-pigmented microbes, or provide biological data beyond the coarsest taxonomic resolution of dominant players. A third problem related to scaling; while many of the critical processes involving microbes occur at scales of microns, their effects may be regional and even global. Thus, our capacity for ocean observation at scales relevant to marine microbes created a third impediment.

Fortunately, technological advances in the decade prior to MMI created new opportunities. Genetic tools had reached the point where genome sequencing was possible and, for the first time, unambiguous microbial identification became possible. Nonetheless, applications of these tools to microbial ecology were few. Genome sequences were complete for only a few species; taxonomic inventory of heterotrophic microbes had hardly begun; and genetics-based taxonomy was lacking for most microbial groups. The 1990’s also marked the widespread recognition of a need for better ocean observation; and the development of cabled observatories and fleets of autonomous vehicles fitted with new *in situ* sensors offered new opportunities for observation beyond cruise-based research that typically provided “snapshot” views of dynamic oceans and their microbial life.

Thus, new tools had appeared on the horizon that could assist in opening the black box, but had not yet been widely applied to the major unanswered questions in marine microbial ecology.

MMI began against this backdrop of opportunity, and the program quickly embraced these new tools as it delved into the ‘who’, ‘how’, and ‘where’ of major marine microbial processes.

MMI Successes

Choice of Marine Microbiology as an Area of Focus

An important success of the GBMF Marine Microbiology Initiative was the choice of marine microbiology as a field for major investment in 2003. As noted, at the time the initiative was being contemplated, the field was just beginning to understand how marine microbes could be significant contributors to the productivity of the oceans. Marine microbial ecology was primed for a major step forward and tools such as genomics and metagenomics had matured to the point where they could be the catalyst. Nonetheless, marine microbiology financial support was only a small component of funding from federal agencies and other sources of marine microbiology funding focused primarily on pathogenic microbes.

The decision of the GBMF to make extensive investments in basic marine microbiology research, and to enable and ensure the use of modern molecular biology techniques for the research, has resulted in rapid expansion in our knowledge of this critical component of marine life and provided key insights that are attracting additional interest and investment.

Choice of People

One key MMI strategy was to create the GBMF Investigators[1] program, which focused on funding people rather than specific projects, and it did so by providing remarkably generous funding to small and highly select groups of established leaders and emerging leaders in marine microbial ecology. The established leaders were selected from several major institutions with strength and commitment in microbial ecology, and although the groups did not include all of the major players in the US marine microbial research community, it included a large proportion of them (Figure 1).

The senior GBMF Investigators, who were established stars in 2003, continued (and continue) to lead key aspects of the marine microbial field with their MMI research. Although there is not a way to determine whether the advances they achieved through MMI might have occurred without MMI funding (leaders by definition, lead, and all of these investigators could claim multiple successes before MMI even began), **there is little doubt that the program significantly accelerated the rate of progress on some of the major questions they addressed**. Moreover, the established leaders all clearly performed very well. In a sense, the choice of established leaders effectively guaranteed success given that all had well-equipped labs with established personnel and workflows, and international reputations that ensured their work would attract top-notch students and post-docs, the interest of outside investigators, and complementary funding from other organizations.

[1] Throughout this report, GBMF Investigator is used to denote the MMI's investment mechanism in 'people' (i.e. the twelve senior and junior PIs that were selected based on their standing and potential in the marine microbiology community). The term "MMI grantee" is used to denote awardees that were funded for specific projects including research, instrumentation/facilities, and data sets.

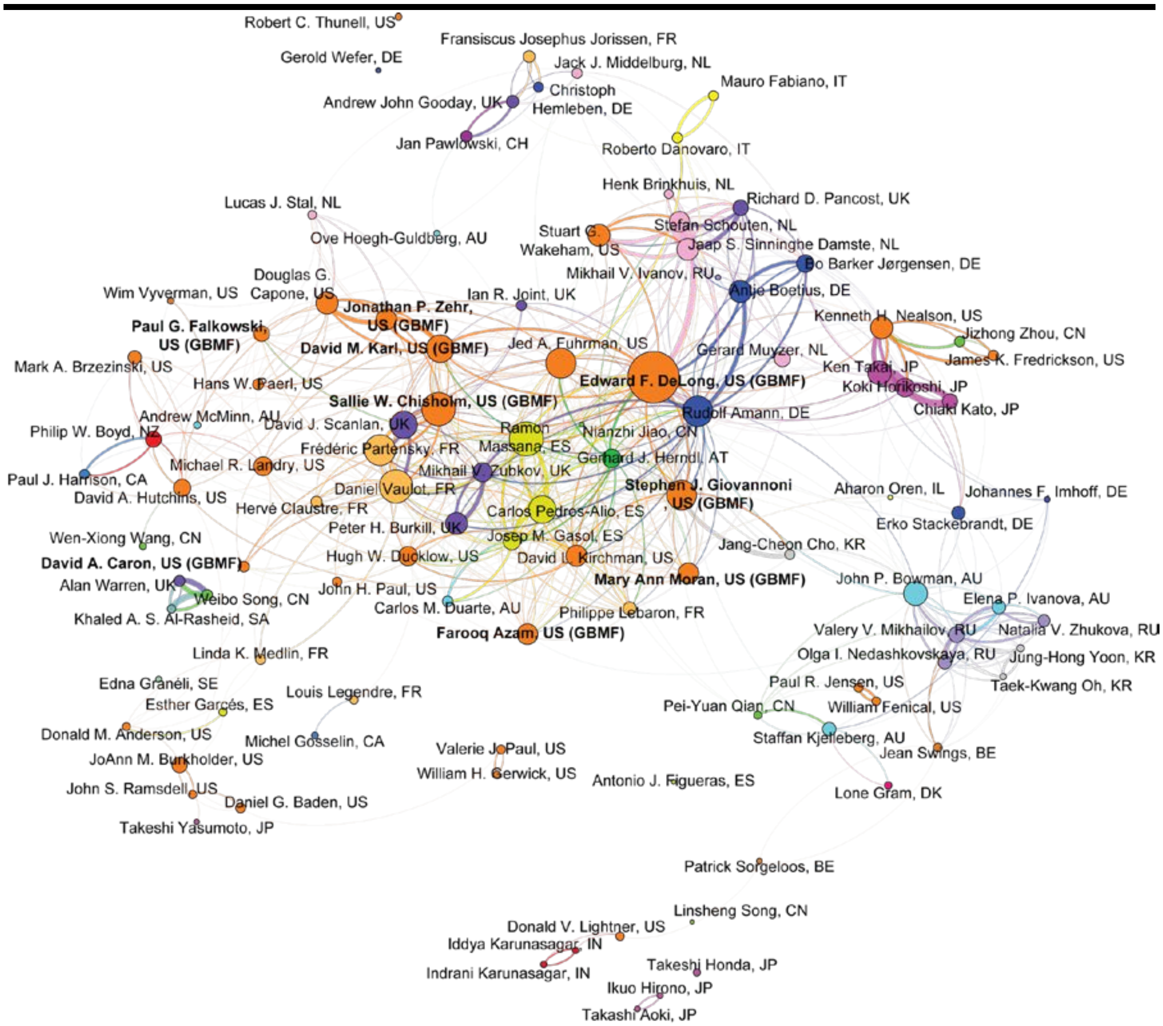


Figure 1. Citation network of the world's most productive researchers in the field of marine microbiology (based on citation count, 1996-2010). This network map provides an overview of MMI grantees relative to the marine microbiology community as a whole (MMI grantees are listed in bold). Colors represent the country of the PI's home institution (orange for US). These researchers were identified based on their number of published papers from 1996 to 2010. The size of the node is proportional to their average weighted in-degree per paper (i.e., to their average number of citations received per paper). Links represent citations given from a citing node (i.e. the source) to a cited node (i.e. the target). Links are colored based on the source color and are proportional to the number of citations between each source and target. Links representing more than 60 citations are show. Source: Science-Metrix using Scopus.

Impacts on the Field

MMI set out to transform the efforts in marine microbiology into a new field of microbial ecology in ten years - an extremely difficult goal in the strictest sense. Realistically, no single entity could be expected to achieve such an ambitious objective in this timeframe. But the program did transform significant aspects of marine microbiology that may ultimately help to transform the field. In a general sense, the most transformative aspect of MMI has been to bring "omics" work (genomics, metagenomics, metatranscriptomics) to the forefront of marine microbial ecology and to support major breakthroughs in microbial observation. Within this section we focus on broad areas where transformation is evident, leaving specific research highlights and discoveries for a later section.

Scientific Impacts of MMI on the Field of Marine Microbiology

- Significant advances in our capacity to identify and observe microbes in their ocean environment, including remote, subsurface locations.

- Major insights into the role of microbial communities in cycling of major nutrients, including nitrogen, sulfur, and carbon

- New tools and strategies to understand gene expression in marine microbes and how that expression influences major ocean processes related to biogeochemical cycles and ocean productivity.

The MMI has also brought recognition and prestige to the field of marine microbiology, as noted in the panel reports and AAAS survey of grantees (Figure 3). One survey respondent summarizes the program's success as follows: "***The MMI has pushed the field of marine microbiology to entirely new levels, particularly in terms of the types of cutting-edge genomic approaches being applied to understanding diversity and functioning of marine microbial communities****.*"

The bibliometrics data shows that the MMI has funded investigators who are major players in the growth of the field of marine microbiology (Figure 2) and, among the funded groups, partnerships and collaborations have grown (see Supplementary Info I).

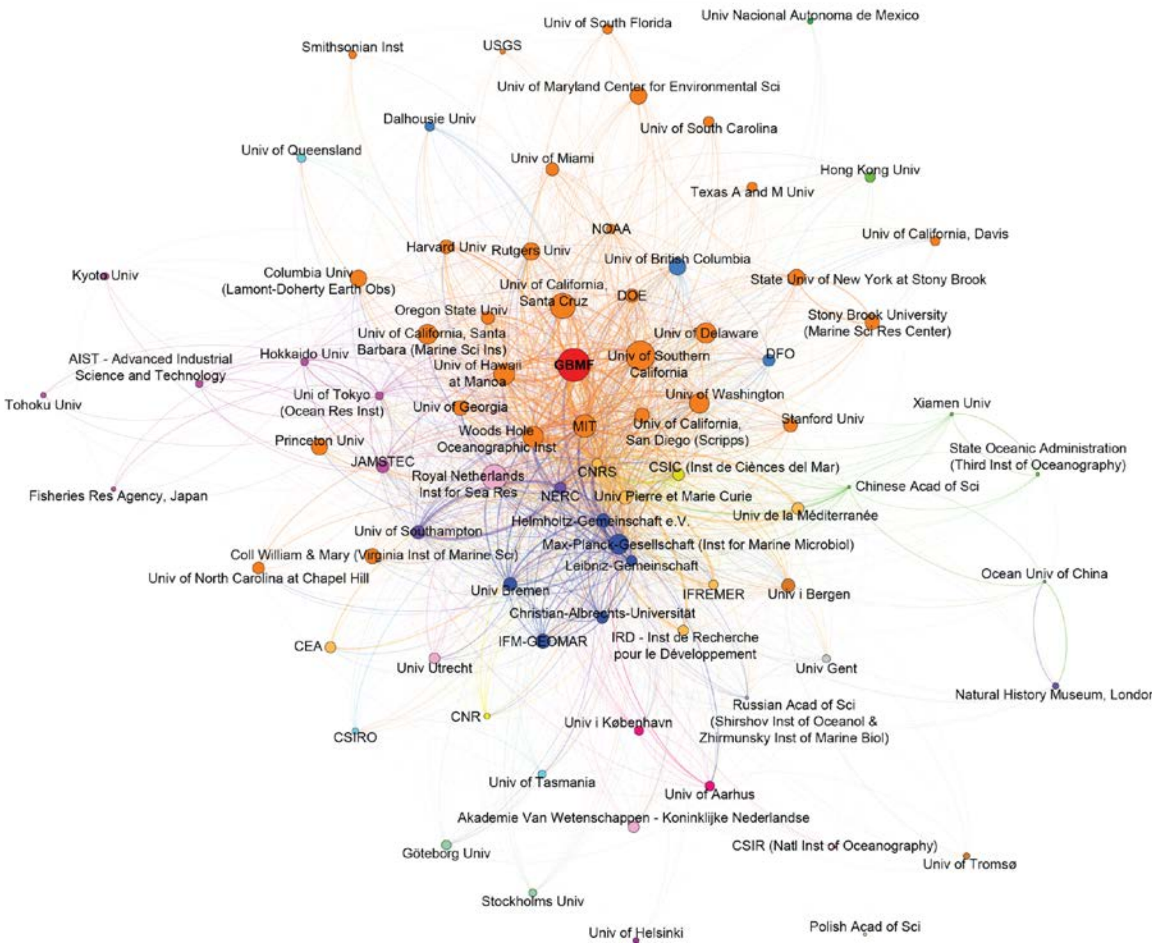


Figure 2. Citation network of the world's most productive research institutions in the field of marine microbiology (based on citation count, 2004-2010). This network map shows that, collectively, that publications by MMI grantees are highly cited by PIs from the leading institutions in marine microbiology. Data are presented for 2004-2010 to match the time period of the MMI. The nodes represent institutions*. The color of the node represents the country of the institution (orange for US). The size of the node is proportional to their average weighted in-degree per paper (i.e. to their average number of citations received per paper). Links represent citations given from a citing node (i.e. the source) to a cited node (i.e. the target). Links are colored based on the source color and are proportional to the number of citations between source and target. Links representing more than 200 citations are show. Source: Science-Metrix using Scopus.

***note**: The GBMF node represents researchers funded by MMI. While a direct comparison to other nodes (i.e. institutions) cannot be made in the strictest sense, the size of the GBMF node shows that MMI researchers as a group rank the highest in average number of citations per paper.

The AAAS panel reports and MMI survey response generally agree that MMI accelerated advances in the field of marine microbiology by enabling high-risk and interdisciplinary research. Qualitatively, this conclusion was captured by several MMI survey respondents:

> *"[MMI provided funding for] discovery-based research programs that would be difficult or impossible to obtain funding for through normal federal agencies"*

"It gave us the infrastructure, e.g. sequencing facilities, the GOS databases, influx flow sorters and the funding necessary to run a laboratory that can take risks and go in new directions. It also gave me the freedom to take a long view of my research goals."

"Provid[ed] resources and funding to support large scale research programs in marine science during a time when federal sources for marine microbial ecology were shrinking. Providing a significant genomic and metagenomic resource through major sequencing programs and bioinformatics infrastructure tailored to ocean research"

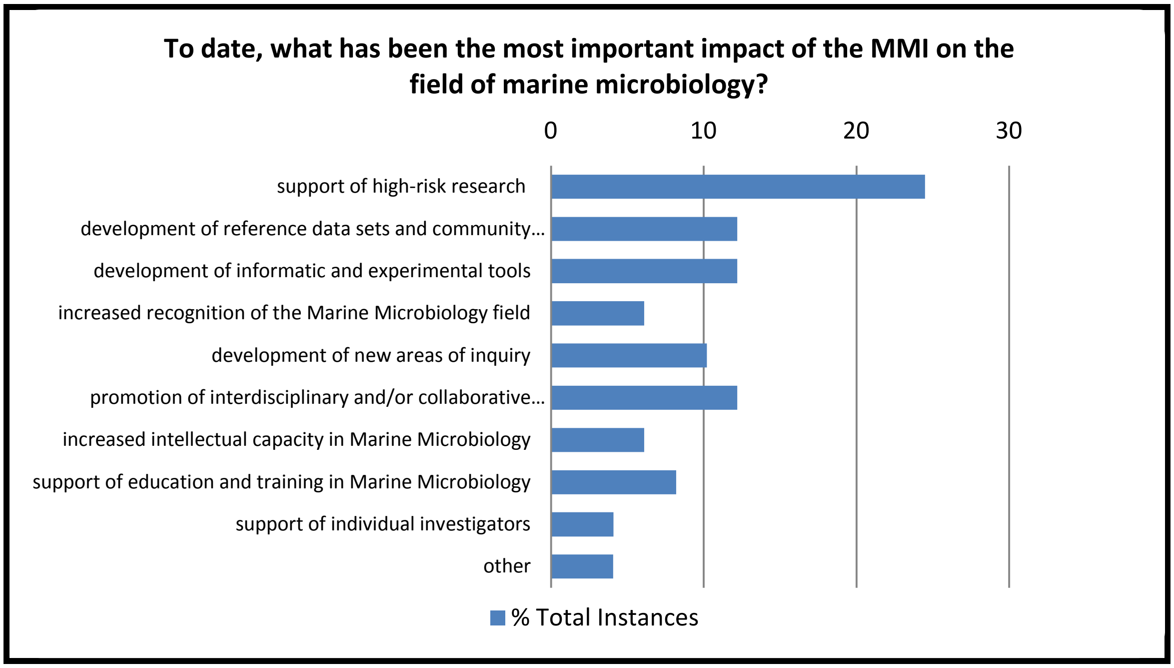


Figure 3. AAAS survey results representing the view of MMI grantees (n= 45). The top responses to the question "What is the most important impact of the MMI on the field" highlighted the support for high-risk and collaborative research, the distinction that MMI brought to the field and the lasting reach from funding tools and data that is shared with the marine microbiology community.

Research Highlights

Major Insights

The MMI grantees made major contributions to the field through insights at three levels: the ecosystem, organisms, and molecular biology/biochemistry. Below are representative examples of the collective advances enabled by the MMI portfolio. The EAC chose to focus solely on the GBMF Investigators in this section (not all MMI grantees) given that these PIs were funded early in the program and had more time to establish results and given the amount of resources that were provided that were dedicated to specific research questions. Accomplishments enabled through other granting mechanisms (e.g. for research infrastructure are discussed further below).

At the **ecosystem** level, GBMF Investigators took on several challenging problems. Zehr addressed the abundance and function of nitrogen-fixing bacteria and Karl focused on a novel process of aerobic methane production. Karl also studied the potential role of phosphites/phosphonates, and Orphan looked at new mechanisms for anaerobic methane oxidation. Orphan also used innovative Magneto-FISH (Fluorescent In Situ Hybridization) to establish simplified consortia from deep-sea sediments. Fe-limitation is an important control on the primary productivity of open ocean ecosystems. Armbrust developed a Fe-limitation index based upon diatom work. The work of Karl and Zehr also focused on the influence of microbial populations on elemental stoichiometry and nutrient flow (C and N, respectively).

At the level of **specific organisms**, Chisholm demonstrated the complexity of the *Prochlorococcus* group and the implications of this diversity for specific environments. Giovanni's study of the most abundant marine microbe, *Pelagibactor*, and Moran's studies of *Roseobactor*, which is so important in coastal systems, brought new insights into the roles of these organisms, as well as insights into how to approach the study of these keystone organisms. King used a marine flagellate as a model to study the evolution of a potential animal progenitor. The use of functional genomics was used to gain insight into diatom stress responses (Armburst), cyanobacteria diel cycle gene expression (Zehr), and S cycling (Moran).

GBMF investigators also researched microbial interactions to a limited extent, with a major focus on the interactions between SRB (Sulfate Reducing Bacteria) and methanogens in the context of anaerobic methane oxidation (Orphan) and on predator-prey relationships between microbe and virus (*e.g.*, Chisholm, Hughes-Martiny). GBMF Investigators used genomic data to investigate potential impacts on the S cycle (Moran), cellular energy conservation (DeLong, Giovannoni), C fixation (Armburst), and methane generation (Karl).

At the level of **molecular biology/biochemistry**, the labs of senior GBMF Investigators Delong and Giovannoni were the leaders in studying a novel light-harvesting mechanism based on proteorhodopsin found in otherwise heterotrophic marine bacteria. Delong had discovered this gene in 2000 and demonstrated its proton-pumping capacity in one γ-proteobacterial clade, and later in 2005 Giovannoni's group observed proteorhodopsin in a SAR11 isolate (*Pelagibacter ubique*). Chisholm explored novel P metabolism genes, Karl studied the potential role of phosphites/phosphonates, and Rohwer explored viral metagenomes.

An important advance for the field was that GBMF Investigators clearly demonstrated the capabilities of metagenomic approaches to studying marine microbes. Before this initiative, many were skeptical that these approaches could be used successfully to advance and refine knowledge of the marine microbial community. **The value of these approaches is now part of the canon of marine microbiology**. Metatranscriptomics, which was used by several GBMF Investigators (*e.g*., Armbrust, Moran and Zehr) is still difficult to do (and thus risky) because of problems in working with RNA and abundance inequalities between rRNA and mRNA. But the work of GBMF Investigators has advanced understanding of this technique.

GBMF Investigators took on extremely difficult challenges, such as the metagenomics of viruses (F. Rohwer), which is as difficult to examine as in prokaryotes. Metagenomics of eukaryotes is even more difficult, but was attempted by Worden.

In summary, the pioneering work of MMI grantees transformed methodologies and approaches deemed high-risk only 8 years ago to relatively tractable and appropriate tools for projects with similar scope and resources.

People

The investment in people, through the GBMF Investigators program, has been substantial and catalyzed major research activities in 12 core PI laboratories and in many associated laboratories supported by MMI funds. Within those 12 core labs MMI supported the training of postdoctoral investigators, graduate students, and undergraduate students as well as numerous other lab personnel managers and technicians. However, this training was very uneven among laboratories, with much greater activity in established labs than in those of new investigators (as would be expected). The number of postdoctoral trainees was especially impressive, during a particularly difficult period in the science job market. With notable exceptions, the number of graduate students was decidedly low for such a major financial investment, but perhaps MMI evolved a deliberate strategy to de-emphasize graduate student training. It may also be indicative of the small number of students that were able to be recruited from the source pool. Multiple undergraduates also trained in the GBMF Investigator's labs.

Unfortunately, the reporting provided on most MMI grants made it very difficult to determine who was trained and the impact of that training. This shortcoming was evident not only for personnel trained (undergrad, grads, and post-docs) but also for the overall impact of equipment and research facilities. For example, there were a few reports of large numbers of people supported but at no point was the information summarized or assessed across the program. In short, the overall impact of MMI training cannot be assessed because the necessary information cannot be extracted from many of the grantee reports.

Multi-disciplinary teams are critical for addressing the overall MMI objective, and there is evidence for good integration across the fields of Paleontology, Physical Oceanography, Ecosystem Modeling, Engineering, Mineralogy, and Bioinformatics. These integrative teams are especially important for a better understanding of the role of microbes in ocean geochemical processes.

Summer Courses, Meetings, Workshops

Although MMI directed the vast majority of funding toward laboratory and field based research programs, it did invest modestly in some non-research specific activities such as summer courses and workshops.

Summer Courses: MMI supported 5 summer training courses at locations scattered from coast to coast. These courses focused primarily on molecular laboratory techniques. Over a three-year period these courses trained approximately 84 students per year, with a heavy emphasis on graduate students using metagenomic tools. Annual meetings of MMI course directors helped to develop synergies and collaborations, including a biogeography experiment that would have been difficult to organize in any other way.

Leveraging of additional funds to support these course offerings varied from excellent (USC, Hawaii) to poor (Hopkins). Although the cost per person ratio for these courses was high (approaching $10,000/head/course), their focus on cutting-edge technologies required significant hands on training with high-end instrumentation. Student feedback, though minimal and largely anecdotal, indicated a high level of satisfaction with the course offerings, and demand for the courses appeared strong. A key weakness is the measurement of impact on trainees (e.g., changes in research capability, retention and/or future success). Courses like these can catalyze new collaborative opportunities and networking, but there was no indication whether such benefits were achieved.

Meetings and Workshops: The EAC understood that GBMF Investigators are brought together once a year to exchange ideas and network. This strategy was thought to be excellent and should be continued. To date, MMI has made only modest use of workshops as a unifying or catalytic tool. Workshops to date covered ocean acidification and new directions in marine microbial ecology; the latter has produced no identified output and the former produced a white paper with no identified impact to date.

Recommendations

- **In the future, greater effort should be placed on standardized course evaluations and tracking of students, and consideration that emphasis on who receives MMI funds be placed at locations with greater leveraging of funds.**
- **Because the networking between projects varied greatly, there could be great benefits in bringing together PIs from all MMI projects as well as postdocs and graduate students with the GBMF Investigators.**
- **Workshops provide an excellent mechanism for cross fertilization and MMI might consider using them more extensively to bring together a geographically dispersed program to facilitate greater synthesis and value added for individual projects.**

Equipment

The MMI invested heavily in equipment infrastructure to ensure that scientists could work with high quality, and cutting-edge facilities. That strategy worked quite well, with some investments showing significant early returns and others showing great promise. The ability of MMI to respond quickly to technology changes and take higher risks than traditional funding agencies in providing new technology, significantly helped to bring advanced, diverse technologies to the marine microbial world and to the scientific community. Some of these technologies, such as high-throughput sequencing, have far broader application and will help to catalyze related disciplines.

Specific details regarding equipment are summarized by the individual review panel reports and will not be repeated here except to note some generalities and highlights. Broadly speaking, the equipment investments can be grouped into large facilities, tools (including datasets, new technology development), and off-the-shelf purchases.

Large Facilities: The **large facilities** are the marine microbial centers of excellence, MEGAMER and C-MORE. (We discuss CAMERA elsewhere in this report, though it certainly represents a significant facility and center of excellence). The MEGAMER laboratory facility at Santa Cruz is now well established and used by multiple MMI-funded grantees, including those engaged in MMI experiments as well as those developing instrumentation, and thus helps to bring MMI granteestogether. MEGAMER is also intended to serve members of the greater oceanographic community through the opportunity to reserve lab space at the facilities. However, it is not clear how many non-MMI researchers have utilized this facility. In addition, MEGAMER is intended as a training center for next-generation marine microbial scientists, but the reporting methods used made it difficult to quantify exactly how researchers trained at and/or benefitted from this facility. Nonetheless, the potential for training, looks very encouraging. Few details were provided regarding the use of the C-MORE laboratory, which established a critical mass of infrastructure needed for a world-class center for marine microbial research. Building delays have placed this facility behind MEGAMER in terms of delivery on potential, but C-MORE has great potential and the future looks promising.

Tools: The **new tools** developed in the MMI **may well represent one of the most significant and enduring legacies of the program**. Multiple examples of new innovations (e.g., ESP) and major advances in others (e.g. *in situ* flow cytometer) could truly transform observation and understanding of marine microbes. Specifically, MMI scientists demonstrated the potential to monitor ecologically important (as well as harmful species), and to monitor gene expression within these species. Because these tools offer remote, long-term, and even real-time potential, they are likely to become major tools for understanding the complex dynamics of marine microbial communities. Some of the newly integrated laboratory equipment (e.g. FISH-SIMS) provides never-before possible measurements that will greatly enhance microbial studies. Although, the MMI has necessarily focused on some very specific questions, the potential of “tool” development for future application to many other important problems is immense.

Off-the-shelf purchases include standard and novel applications of proven technologies. Through MMI, a variety of labs across the US (and in one instance in Chile) were equipped with high quality equipment necessary for field and/or laboratory experiments and measurements. All of these decisions appeared very sound, and will undoubtedly improve and accelerate marine microbial research at those locations. In some cases, PIs found new applications for existing technologies to provide new ways of “seeing” microbes (both literally and figuratively), and some of these applications show great promise.

Datasets: The MMI datasets represent an important aspect of infrastructure with many potential future applications. The CAMERA database, which is clearly the largest investment (discussed in the next section), illustrates that multiple users can benefit from shared data. The utility of MMI data beyond CAMERA and GENBANK are unclear in terms of ongoing data sharing, ease of access, and future potential, though different projects report multiple examples of online data pipelines (e.g. *nifH* and *Prochlorococcus* genomic and gene expression data). There is also mention of protocol development (e.g. ESP, primer design) that will be invaluable though the mode of access and linkage to other protocols remains unclear. **Data and standardized**

methodologies could be major legacies of the program but will require planning and effort to maximize their utility.

In many instances, investments in tools (and datasets) already show solid returns, with interesting publications and some intriguing findings that advance the field of marine microbial ecology. The broader impact of this infrastructure will likely emerge over time as MMI grantees and additional researchers take advantage of the instrumentation available, and others engage in the use of the novel applications to address new questions in marine microbial ecology and beyond. But, the real impact may be difficult to discern because the reporting mechanisms do not seem to require identifying other users and impacts. Thus, without changes to the reporting scheme the broader impacts will not be fully appreciated.

Recommendation

In order to maintain research at the forefront of the field for Phase II, MMI must prioritize the maintenance of this cutting-edge equipment, along with upgrades as technologies develop. Planning for the long-term sustainability of these facilities must be a central element of legacy planning (see below) as MMI winds down.

CAMERA

The vision for MMI-supported CAMERA was to create a central data repository together with bioinformatics tools to serve the needs of the marine microbiology community and other users. The program was established in 2004, with the first release of the web portal in 2007 to support the publication of the Global Ocean Survey dataset from Craig Venter. Since then, the web portal has been modified in response to user feedback, with a re-launch of the site in 2010. In March, 2012, the AAAS review panel conducted a detailed assessment of CAMERA functionality, cyberinfrastructure, impact, and service to the marine microbiology community. The findings from that report were used to develop the EAC's recommendations on future options for the program. Table I briefly summarizes the main strengths and challenges for CAMERA.

Table I. Findings from the AAAS CAMERA Review Panel Report (March, 2012)

Strengths include the offering of unique services	**Challenges to scale up and serve the community**
• exceptionally well-curated metagenomics datasets are a resource for comparative studies by the research community • offering BLAST searches (unavailable elsewhere due to excessive computational intensity) • web portal allows users to customize their own work flows and make sophisticated data queries • personal communication and one-to-one collaboration provided by CAMERA staff to help researchers • ~30 power users* that use CAMERA for research and publications	• capacity of system will not match data-intensive science of Phase II • workflows are costly and current portal technology must be upgraded • balance between maintaining infrastructure on the cutting edge, and serving the needs of both high-end and naïve users • consulting capability cannot scale much beyond its current level without a great deal of additional staff • availability of a range of other databases and bioinformatics tools to the marine microbiology community

*data provided by CAMERA team

Current Trends and Considerations: As MMI transitions to Phase II, several questions arise regarding the future of CAMERA. The first is whether CAMERA can adequately meet the needs of a critical mass of users in the marine microbiology field with the resources that the GBMF can make available, while simultaneously remaining on the cutting-edge and facilitating the next phase of marine microbiology research. As it has evolved, CAMERA has become somewhat of a "boutique" database that serves the needs of a relatively small number of loyal users at a very high level. There is great value in providing this service. However, the MMI originally envisioned that CAMERA would become the genomics database of choice, not only for the MMI but for a broader community. Several factors conspired against this vision playing out as planned. Consumers of genomics information are driven to find solutions that enable their laboratories to complete data analysis as rapidly and easily as possible. This often means using multiple database resources. Once a user finds a data analysis solution, their loyalty becomes difficult to change. Recapturing potential CAMERA users who have gone elsewhere may therefore prove difficult.

Another critical element in any decision about CAMERA's future is whether it can develop a business model that will allow for its sustainability. The increasing throughput and decreasing costs associated with generating DNA sequence data have outstripped Moore's law to the point that genome/metagenome analysis has become a standard assay in many environmental studies. As datasets get larger and more disparate, the cost to store and integrate these data continues to increase. This particularly vexing problem cuts across all scientific communities, threatens to impede scientific progress, and is being discussed by all Federal agencies that fund "-omics" research. While additional funding for bioinformatics tool development and personnel will be required to support the broad scientific community, it is still not clear how best to fund such large initiatives in perpetuity. This issue urgently needs thought leadership, and the GBMF might consider convening major potential funders, both federal and foundation, in a series of meetings to discuss the larger issues of super databases and access to high-end tools, using experience with CAMERA as a learning tool.

Finally, the advent of next-generation DNA sequencers has democratized sequencing and moved this activity away from large genome centers and into the laboratories of individual investigators. This shift also happened within the MMI as it provided next generation sequencers to some of its investigators to facilitate evaluation of these new technologies in the context of metagenomics studies. The EAC views this step very positively because it creates greater flexibility in addressing priority research questions as they emerge. This shift also facilitates the training of students and post-doctoral fellows in large-scale sequencing approaches. Given this change, the EAC believes there is value in further developing the capability for data analysis at local levels by experts in specific areas of research, as an adjunct activity to a more centralized database model exemplified by CAMERA. The best long-term solution to the data deluge problem will likely require multiple interacting nodes of expertise.

CAMERA section continues on next page

Table II. Options for the future direction of CAMERA and the likely consequences to the community and Funder both positive (+) and negative (-). The current status of the program includes Database and Tools (3rd column from the right). The database involves maintaining a data repository for genomics, metagenomics, and other data while tools include bioinformatics tools and workflows. Expansion of CAMERA would accommodate more data and the development of additional analytical tools. Within each option, a range of models exist and decision points need to be addressed including who the target audience is, stakeholders involved, computing needs, and financial resources available. The Data Coordination Center (far right) is conceptually a different approach and is an option that is recommended by the EAC.

Options for CAMERA

	No CAMERA	Tools Only	Database Only	Database + Tools	CAMERA Expansion	Data Coordination Center
+	This decision frees up resources for other MMI research	Continued availability of the CAMERA tool kit will facilitate downstream data analysis, especially for loyal users. CAMERA does offer a few capabilities not readily obtained elsewhere.	Availability of all relevant genomics and metagenomics data in one location facilitates comparative analysis and ensures that adequate quality control can be applied	This is the current model and will be least disruptive to power users in the short to medium term	Increases the likelihood (but does not guarantee) that GBMF-funded "-omics" research will be fully leveraged and integrated. Protects GBMF investments to date.	Establishment of a resource that contains information about all types and locations of data relevant to the MMI community would be of great value and fill a current void
-	Current users will not readily be able to continue ongoing CAMERA-enabled work	Focus only on tools will require users to find relevant datasets elsewhere. This may not be easy.	Focus only on database function will require users to find relevant tools elsewhere. Data transfer, particularly for large datasets may be difficult.	The current model will not scale as the amounts of genomics and metagenomics data increase	Not a sustainable model; thus, additional short-term investment will likely not pay off long-term	Users will be required to find analysis tools elsewhere. This will be easier for the more sophisticated users.

Recommendation

For the reasons outlined above, the EAC does not recommend continuing CAMERA in its present form. If MMI chooses to discontinue CAMERA, it will likely need to develop a transition plan that minimally disrupts current users. One possibility for serious consideration is to evolve CAMERA into a Data Coordination Center to assist scientists in (a) submitting data for long-term storage in accordance with the expectation of the GBMF, (b) in finding and linking all types of data related to marine microbiology, and (c) in ensuring data quality and reliability. The Data Coordination Center could also collaborate with other Federal and Foundation-funded projects in database development and management. This strategy would deliver an extremely valuable contribution to the field as the size and types of datasets continue to increase.

MMI Management

The EAC chose to focus its management review on program design and implementation, which includes MMI goals, grantee selection/review processes, and grants management. The EAC analysis is based on the data archive provide by MMI, interviews with MMI staff, and a survey completed by MMI PIs and co-PIs. We start with a look at Phase I implementation and outcomes, then consider evolution of the program design for Phase II, and conclude with recommendations forPhase II implementation.

Phase I Program Design and Implementation

Goals: Originally, the MMI program laid out a very broad vision with goals and timelines that were not clearly understandable. The transformation of the entire discipline of marine microbial ecology, while laudable, exceeds the capacity of any single agency operating over a decadal time scale. A program of this magnitude should outline specific goals framed with detailed milestones to provide a mechanism to measure whether the program remains on track towards attaining specific and realistic research goals.

Approach: The original overall concept in Phase I of the MMI was primarily to choose established PIs with a proven track record from the marine microbiology field for its three strategies: GBMF Investigator Awards, Multidisciplinary Expansion Awards and High Impact Research Awards. This approach is analogous to that used by the Howard Hughes Medical Institute (HHMI) and the Office of Naval Research (ONR). The other main approach was to encompass “omics” as an integrating technology across a wide range of scientific questions. The MMI took a strategic approach with its focus on modern technologies to spur advances in marine microbiology. One of the trade-offs of this approach, as noted in the panel reports, is the emphasis on ‘omics’ altered the perception of the importance of other, more traditional molecular biology approaches. These other approaches will also be needed to answer the long-term goals proposed by the MMI.

Grants management: With several changes in program management staff, reporting on grants by principal investigators was not reliable and uniform, as noted elsewhere in this and other individual panel reports. This variability made it difficult to assess the impact of MMI funding beyond the publications. The GBMF (and this review) may be underestimating the full impact of the MMI investment as a direct result of lack of data assembled by the grantees and the program office.

Outcomes: Although the process for selecting the MMI granteeswas not transparent to either the research community or the independent review panels, it was a highly successful approach for supporting leading researchers in marine microbiology and producing publications in top tier journals, as verified in the bibliometrics report developed by ScienceMetrix Corp (see supplementary info) and commented on earlier in this report.

The success among the junior group of emerging leaders appeared more variable. The process for choosing emerging leaders was also unclear, but in this case, the more substantial gamble produced some clear wins. Although the choices of emerging leaders were clearly reasonable and defensible, the very large grants to new and largely unproven young faculty, along with correspondingly high expectations, produced uneven results. Some investigators did quite well and proved excellent investments. Because many emerging MMI granteeslacked the physical infrastructure (fully equipped labs and field equipment) and intellectual infrastructure (graduate students, seasoned technical support) of established leaders, some struggled to purchase equipment in a timely fashion, recruit students, and produce successful outputs in proportion to the unusually generous funding provided. As a result, no-cost extensions were often needed, timelines (which were never defined in detail) showed slippage, and the deliverables up to the time of this review, were sometimes below expectations. Importantly though, most or all of the emerging investigators will likely produce solid and, in some cases, important research.

Phase II Program Design and Implementation

Goals: The EAC panel felt that MMI made significant progress in identifying appropriate stretch goals for the second phase of the program. The revised goals are logical, more realistic and attainable over the remaining lifetime of MMI.

Approach: To launch Phase II, MMI departed from its original grant making approach and instead asked the community to submit ideas. The request was followed by an invitation to submit proposals. This approach of allowing current MMI awardees as well as outside investigators to compete for available funds resembles NIH and NSF solicitations. It is too early to tell whether this new approach will prove more effective, but the EAC views this new Phase II strategy as a positive step that will address some of the perception issues about the MMI (discussed below).

The EAC notes that the Phase II approach appears more outcome-oriented and thus more risk adverse, than the Phase I approach. On the other hand, the Phase II approach is more tightly connected to the MMI program's time-phased outcomes. **The challenge, of course, is to match individual proposal outcome goals with the MMI 2015 and 2019 time phased outcomes without becoming too prescriptive and thus too risk adverse. The future goals, at least on paper, appear more constrained (i.e. science focused rather than community building or student training).** If this is intentional, the outcomes seen from Phase I funding – research publications (the primary outcome of funding *People*) versus unconstrained outcomes with broad dissemination (the primary outcome from funding Tools and Data) - should inform the funding strategy employed for Phase II.

MMI will also need to determine whether the long-term (2019) targets of Phase II time-phased outcomes actually represent specific goals. If so, how will staff internally monitor progress towards the long-term targets, as outlined in the very detailed and specific 2019 time-phased outcomes? It is not clear how the single investigator approach, a key part of the Phase II budget, will ensure success in meeting these specific goals.

The Responsibility of GBMF as a Major Funder of Marine Microbiology

As noted above, the perception of the MMI is a very important consequence of the GBMF providing such a large percentage of the marine microbiology funding. The broader marine microbiology community needs to understand the decision-making processes for award selection, and how these decisions track with the program's long-term, targeted time-phased outcomes.

The move to accept proposals from the community at-large serves another important purpose, which is to build the relationship between MMI and the broader marine microbiology community. The individual panel reports noted dissatisfaction with the approach the MMI took in selecting grantees in Phase I, from elements in the research community. Although dissatisfaction is to be expected from those who were not selected, the community as a whole exerts influence on perceptions of the funding. In order for the GBMF to accomplish its goal of transforming marine microbiology as a whole, broad community buy-in is a requirement. Having an open call for ideas along with the GBMF Investigator competition as part of Phase II, assists in reaching that goal, but will not be sufficient to counteract the perception that funding is reserved for a "club".

Even with a broader call for participation, if the selection process is perceived to be uninformed by broad expertise in the field of marine microbiology, the perception problems will be exacerbated. In fact, among the MMI grantees who answered the AAAS survey, 44% stated that the Phase II process was not transparent, indicating that current methods for communicating to the community are not optimal. This concern is relevant given that Phase II targets must include more representation by a broader part of the scientific community (e.g. marine microbial ecologists). The EAC also identified multiple issues during the review that could have been avoided by soliciting advice from marine microbial specialists other than grantees. An advisory committee could provide invaluable advice to the MMI program in thinking through long-term issues and strategies for success of the program and interactions with the marine microbiology community as a whole. This committee could serve as ambassadors for the program to the broader scientific community as well. Such a committee could also be useful in providing input into the next program review. It could also contribute to GBMF thinking (along with their Science Advisory Committee) concerning whether to extend the program beyond the current five year Phase II into new areas of investigation or whether to assist in planning to sunset the program.

Recommendations

- **The EAC recommends that the GBMF find ways to bring the broader marine microbial research community into their advisory process. One approach would be to create an MMI Science Advisory Committee comprising experts that report directly to the MMI program staff.**

- **The awardees in Phase I were experts in specific fields, however, for Phase II to succeed, the program will need additional areas of expertise to meet its long term goals. For the MMI to reach its 2015 and 2019 time phased outcomes (microbial interaction and nutrient flow) the program must engage researchers from other areas such as biogeochemistry and nutrient dynamics.**

- **Though some elements of the MMI program appeared well aligned, others did not. The reports created an impression of many strong and loosely interlinked projects rather than an integrated program. As the program moves forward a streamlined mechanism for identifying the intellectual output and other scientific contributions is needed and timeliness of report submission is essential. The EAC had a sense that the impact of the program was probably much greater than that suggested by the uneven and often incomplete reporting framework.**

Continued on next page

Recommendations (cont.)

- **MMI staff should help to coordinate and assist in networking the individual Phase II proposal awardees so that they *align as a group* with the new long term 2019 time-phased outcomes, given that these targets are quite specific.**

- **MMI should insist on uniform templates for both financial and science reporting (for example, most financial reporting is submitted using a template provided by the PI's institution). MMI should coordinate and enforce this policy across the entire program and identify a party responsible for this oversight. An enforcement strategy (e.g. 10% funding holdback may be necessary to achieve full compliance.**

- **Slippage in timelines (albeit vaguely defined) created significant delays, particularly among young investigators. While some budget flexibility is appropriate to address more of the diverse sub-fields and investigator experience levels necessary in Phase II, careful tracking of milestones could reduce the need for repeated no-cost extensions and delays in moving toward research outcomes. Thus, more attention to clearly defining budget/work timelines for investigators may help to minimize delays and identifying opportunities to redirect funding on stalled or unproductive projects to emerging opportunities.**

Remaining Opportunities

The MMI program focused on some key elements of microbial ecology and achieved notable successes, primarily (though not exclusively) in addressing the roles of single species in nutrient cycling by blue water, surface layer microbes. The complexity of the problem likely necessitated such a focus, but this strategy leaves many opportunities for future study. The program may wish to consider how to expand their work to address coastal environments more explicitly, deeper waters and sediments – all of these environments contribute to microbial regulation of nutrient cycling and trophic structure in the world's oceans. Arguably some of the most important processes occur in coastal waters and in sediments, particularly from a human perspective (fisheries yields, hypoxia and eutrophication, etc.) And, of course, deeper waters encompass some 90% or more of Earth's biosphere.

Perhaps the most striking remaining need in a program that seeks to transform the field to microbial ecology is a more inclusive and comprehensive examination of how key **microbial groups interact with a wide range of other organisms**, from many other microbes, through grazers and up through the food web. To date, the program has largely ignored interaction with higher organisms. Microbial population dynamics must depend to some extent on these interactions, and a thorough understanding of the microbial role in nutrient cycling presumably demands such information. Similarly, the noteworthy efforts within MMI to consider viruses could be extended to consider viral impacts on microbial (and thus nutrient) dynamics, which some studies suggest could be quite considerable. The goal of achieving a "transformable" program hinges on strengthening the "ecology" component of the program, which can currently claim some clear victories on this front, but also many gaps.

Noting the positive reception that the DARWIN modeling received by the review panel, the use of models could be expanded and additional measurements (e.g. field mortality through viral and grazing loss, etc.) added to expand the current program from its rather narrow focus. This is particularly important if the goal is to understand microbial and nutrient dynamics in multiple systems. Even the best models must be informed by reality, and the translation of multiple scattered studies, some field-based and others lab based, could benefit from a stronger interaction with modelers in defining data needs and potential ecological/environmental drivers of ecological and even physiological change.

One other opportunity that could substantially raise the profile of the program relates to changing oceans and the relative impacts of human and natural perturbations. The program may consider this area too controversial or applied, but it certainly represents one of the greatest environmental issues of our time and microbes sit at the core of ecological change. Such a focus would benefit greatly from strong interaction between modelers and field biologists.

Recommendation

Though MMI cannot encompass all aspects of marine ecology, it should prioritize which remaining opportunities are essential to attaining Phase II goals and define a strategy to address those opportunities in the remaining lifetime of MMI. Whether these opportunities focus on human impacts or other topics will help to determine the scope of impact of MMI. A strategy to achieve that impact should be developed.

Legacy Strategies

MMI began with the extraordinarily ambitious objective of transforming marine microbiology to marine microbial ecology. Earlier in this report, we suggested that the initial objectives, while laudable, were most difficult to attain and that the vision and goals became clearer and more realistic as the program developed. But we are left without a clear plan of how the MMI envisions its enduring legacy. At the end of the MMI in 2018, what will be its crowning achievements?

MMI researchers report a long list of discoveries, new tools, and publications that will persist long after the program ends. As an enabler, accelerator, and catalyst, MMI has much to be proud of. Indeed, even without further work the lasting legacies of MMI will include a large number of publications, a cohort of students trained in MMI techniques , cutting edge equipment that includes some really exciting new tools such as ESP and FlowBot, facilities such as MEGAMER, and an influential group of PIs leading aspects of microbial ecological research. But is there an MMI succession/sustainability plan for all these successes? None is evident. Moreover, neither the trainees (from training course graduates to MMI graduate students) nor the publications appear to be well tracked, significantly compromising their contribution to the MMI legacy.

Despite some clear wins, the scope of the MMI program and its legacy could be significantly enhanced . GBMF and MMI staff leaders, along with funded Investigators, should consider whether they want the program impact to extend beyond marine microbial ecologists and, if so, whether they should develop a framework and detailed work plan to ensure that this occurs. They should also consider whether it is possible to transform a discipline through a series of independent publications, generally strong in content but weakly cross-linked and published in a wide range of journals. The various individual review panels that evaluated the MMI program clearly felt that although the basic research outputs have created an impressive foundation on which to build, the “transformative” impact of the program could be significantly greater. **In short, a carefully considered, well-resourced synthesis plan with clear targets requires several years of commitment and effort, and must begin well in advance of the program end**.

The publication of wide ranging articles, many in prestigious journals, ensures that other marine microbial specialists will recognize MMI work. But if the program wishes to transform the field, additional efforts will be necessary. The first question to ask is “who is the audience” that needs to be aware of the transformation? Once MMI has answered this basic question they will be far better positioned to ensure they reach that audience. Primary publications and scattered meeting presentations help to ensure the specialists know what has been accomplished, but what about marine ecologists more generally, or educators, or ocean policy and conservation specialists?

The first group to consider is the marine microbial research community beyond MMI. MMI has clearly contributed significantly to the field, but “transformation” requires persuasion of those whose interests lay beyond the detailed identification of microbes and their impacts on a few aspects of marine ecology (nutrient cycling, for example). Are synthesis papers, reviews, or even textbooks a planned mechanism to bring together the different elements of MMI into a coherent package that refocuses the field? MMI might consider special sessions at Ocean Sciences, ASM or ESA meetings during the last few years of the project that extend beyond individual presentations and include talks that **unify the program’s discoveries and conclusions to give a**

coherent story for the program. Special volumes of journals focusing on common themes within MMI could similarly add to a unified presence.

A second strategy would be to improve data availability. CAMERA is examined elsewhere in this report but improved and cohesive availability of all data forms would help expand the impact. Realistically, a single database may prove impractical at this late stage, but even a central web page of data links could help. Similarly an MMI webpage with appeal beyond MMI applicants could include the following elements: data linkages, project personnel (including PIs, students, technicians and postdocs) and their expertise, and perhaps most importantly a searchable bibliography of all MMI published papers. All of these tools would increase MMI visibility within and beyond the marine microbial community, and help to integrate MMI scientists and their findings with the non-MMI community by making the program more transparent and outward looking.

Further reach could be achieved with greater presence at meetings like AAAS, where MMI-led sessions could raise the profile of marine microbial ecology outside of ocean science. Although MMI findings have significant implications for policy-related issues, including climate change, there is no evidence the program has tried to communicate that information.

If other scientists and funding agencies are expected to participate in a newly refocused – and extremely important -- discipline once MMI ends, serious thought (and work) will be needed to make that happen.

Elsewhere in this review we suggest an MMI Scientific Advisory Committee comprising marine scientists that include some marine microbial expertise. This SAC could play a key role in synthesis and in maximizing impact by helping to create a vision plan that MMI scientists can then execute. Such efforts could go a long way toward addressing the problem of long-term sustainability of the MMI research effort and community as well as the MMI legacy.

Finally, MMI needs to think about the long-term future of this field after MMI funding ends. If successful, MMI will have sponsored research that clearly shows the importance of marine microbes in the trophic structure, disease, biodiversity and nutrient cycling of the ocean and, through these impacts, in other larger concerns such as food resources and climate. MMI will have been the dominant source of funding for a field that is now considered essential.

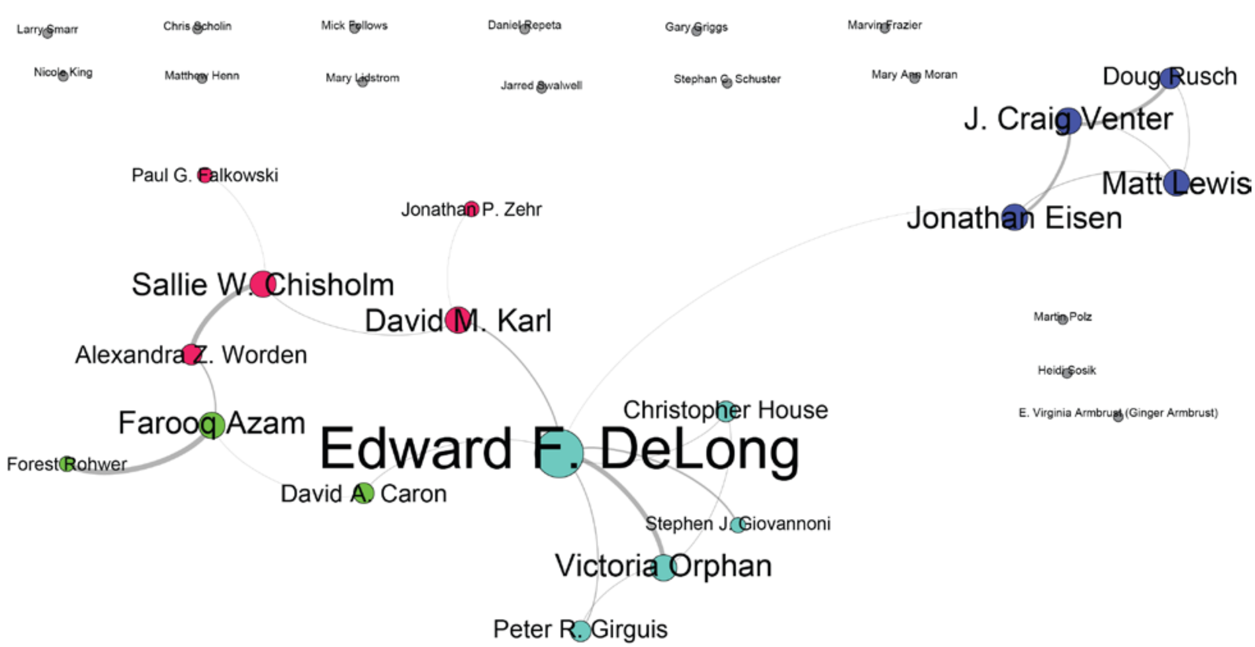
Recommendations

- **To maximize the impact of the program, MMI should develop a synthesis plan and identify the MMI scientists who will play a leadership role in the implementation of that plan. That effort requires that MMI define their target audience and then develop a well-defined and specific roadmap to ensure that MMI discoveries and conclusions reach the desired audience(s). Ideally that synthesis plan should consider which metrics can be monitored to assess impacts and success with the target audiences.**

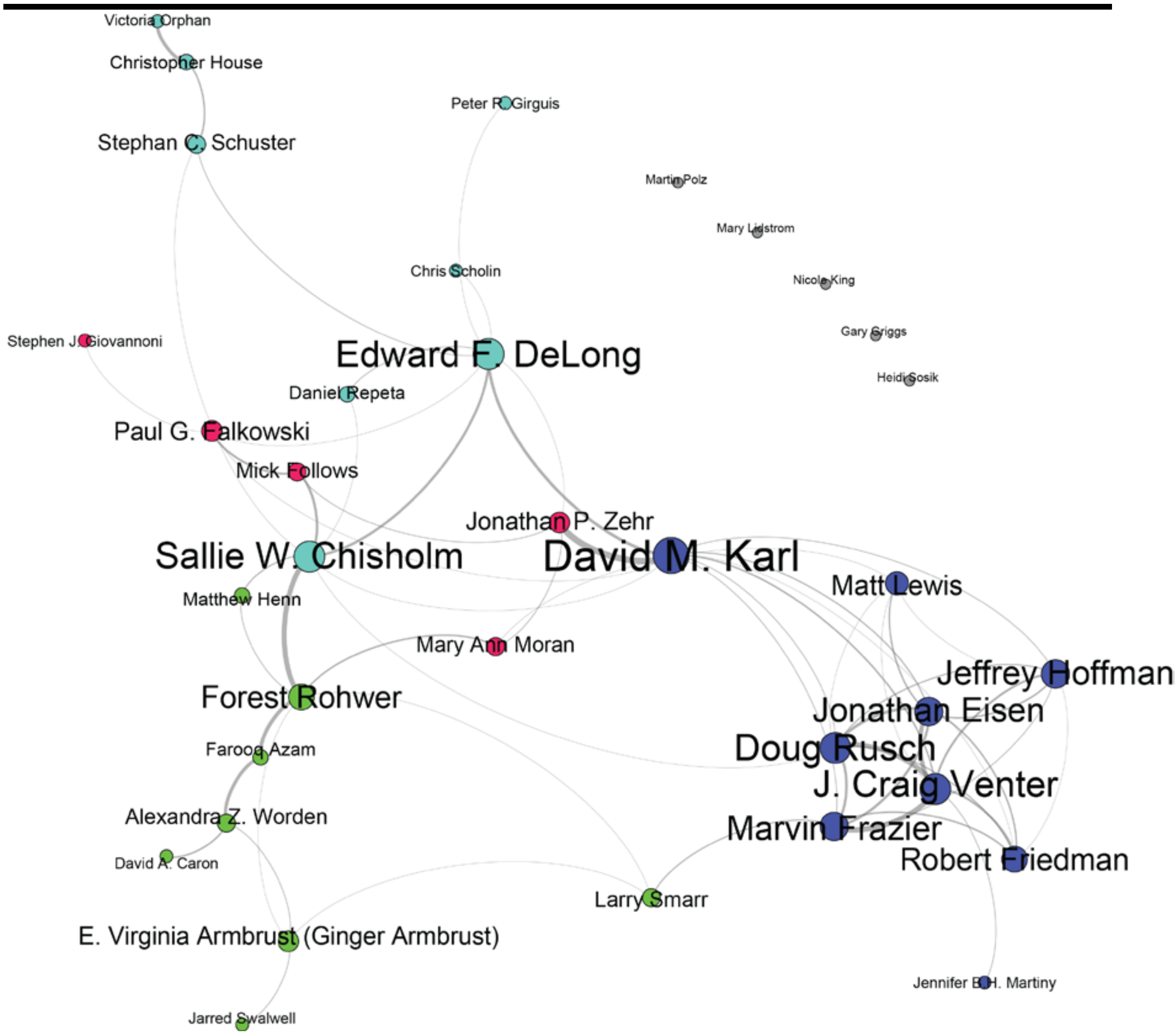
Continued on next page

Recommendations (cont.)

- **MMI will end, and if there is hope for succession through other funding mechanisms, a specific succession plan should be developed before MMI funding is completed and participating scientists retreat to their respective geographic locations. This plan should identify research leaders willing to spearhead any follow-on initiatives as well as detailed plans for how such a program might be funded.**



Collaboration network of GBMF-supported researchers (PIs only) in marine microbiology **prior** to receiving MMI support **(2001-2007)**. Nodes represent MMI-supported researchers. Researchers were colored using a clustering algorithm for uncovering communities in social networks. The size of the node is proportional to their in-degree (i.e. the number of researchers to which they are linked in the network). Links represent collaborations, which are proportional to the number of co-authored papers between researchers. Source: Science Metrix using Scopus.



Collaboration network of GBMF-supported researchers (PIs only) in marine microbiology **during the period** of MMI support **(2007-2010)**. Nodes represent MMI-supported researchers. Researchers were colored using a clustering algorithm for uncovering communities in social networks. The size of the node is proportional to their in-degree (i.e. the number of researchers to which they are linked in the network). Links represent collaborations, which are proportional to the number of co-authored papers between researchers. Source: Science Metrix using Scopus.

Supplementary Info II: Summary of Publications by GBMF Investigators/MMI Grantees

Table I. Subfields and main journals in which GBMF matched papers were published (2004-2010)

Subfield	Papers	Journal	Papers
Microbiology	179	Environmental Microbiology	65
General Science & Technology	94	Applied and Environmental	30
Marine Biology & Hydrobiology	59	ISME Journal	30
Bioinformatics	19	Nature	29
Developmental Biology	19	PNAS	26
Meteorology & Atmospheric Sciences	18	Science	25
Oceanography	18	Limnology and Oceanography	18
Ecology	8	Journal of Bacteriology	15
Evolutionary Biology	8	PLoS ONE	14
Geochemistry & Geophysics	7	Journal of Phycology	13
Biochemistry & Molecular Biology	4	Aquatic Microbial Ecology	11
Biotechnology	3	Int J Syst Evol Microbiol	8
Mycology & Parasitology	3	Nature Reviews Microbiology	7
Agronomy & Agriculture	1	Marine Ecology Progress Series	7
Distributed Computing	1	PLoS Biology	7
Education	1	Limnology and Oceanography:	6
Microscopy	1	BMC Genomics	6
Optics	1	Ecology Letters	5
Paleontology	1	Global Biogeochemical Cycles	5
Plant Biology & Botany	1	Geobiology	5
Software Engineering	1	Deep-Sea Res Part II-Topical	5
Toxicology	1		

Note: The classification of papers by subfield is based on Science-Metrix' journal-based taxonomy of scientific research (http://www.science-metrix.com/OntologyExplorer/#).

Source: Computed by Science-Metrix using Scopus

Appendix I: EAC Member Biographies

External Advisory Committee Members

Gary Borisy is the President and Director of the Marine Biological Laboratory. Dr. Borisy brings a wealth of scientific expertise and administrative experience to the MBL. At various times throughout his career, Dr. Borisy has spent time at the MBL, conducting research; collaborating with scientists; and participating in some of the MBL's educational programs. Dr. Borisy became the laboratory's 13th Director in 2006. Previously he was Associate Vice President for Research and the Leslie B. Arey Professor of Cell and Molecular Biology at Northwestern University's Feinberg School of Medicine. He received his B.S. and Ph.D. from the University of Chicago. After serving a postdoctoral fellowship at the MRC in Cambridge, England, Dr. Borisy joined the faculty of the University of Wisconsin, Madison, rising through the professional ranks to Chairman of the Laboratory of Molecular Biology and Perlman-Bascom Professor of Life Sciences, before moving to Northwestern in 2000. Dr. Borisy is the author of more than 200 papers, the editor of two books, and has received numerous professional honors, including an NIH Merit award and the Carl Zeiss award from the German Society for Cell Biology and the Distinguished Alumni Award from the University of Chicago. He is a member of the National Academy of Sciences and the American Academy of Arts and Sciences and a past President of the American Society for Cell Biology

Claire M. Fraser-Liggett is Director of the Institute for Genome Sciences and a Professor of Medicine at the University of Maryland School of Medicine in Baltimore, Maryland. She was previously the President and Director of The Institute for Genomic Research in Rockville, Maryland. Dr. Fraser has played a role in the sequencing and analysis of human, animal, plant and microbial genomes to better understand the role that genes play in development, evolution, physiology and disease. She led the teams that sequenced the genomes of several microbial organisms, including important human and animal pathogens, and as a consequence helped to initiate the era of comparative genomics. She has served on a number of National Research Council committees on counter-bioterrorism, domestic animal genomics, polar biology, and metagenomics. Dr. Fraser-Liggett has more than 220 scientific publications, and has served on committees of the National Science Foundation, Department of Energy and National Institutes of Health. She received her PhD in pharmacology from State University of New York at Buffalo.

Robert B. Gagosian (**EAC Chair**) was appointed the first President/CEO of the Consortium for Ocean Leadership. As President, Dr. Gagosian oversees the management of major research and education programs, accounting for roughly $250 million. Previously, Gagosian served as Director of the Woods Hole Oceanographic Institution (WHOI). A position he held from 1994 until 2006, following a distinguished career as a marine geochemist that included five years as Chairman of the Chemistry Department, six years as WHOI Director of Research and two as Senior Associate Director. As a research scientist, Gagosian studied organic substances produced by marine organisms and their transport and transformation as they disperse through the water column to the seafloor. Gagosian completed a bachelor's degree in chemistry at the Massachusetts Institute of Technology, and a Ph.D. in organic chemistry at Columbia University. Among his numerous distinctions, Dr. Gagosian has served as a Faculty Fellow of the World Economic Forum in Davos, Switzerland, the Science Advisory Panel of the U.S. Commission on Ocean Policy, and commissioner of the U.S. National Commission for the United Nations Educational, Scientific, and Cultural Organization. He is an elected a Fellow of The American Academy of Arts & Sciences and has served on a wide variety of visiting and advisory committees and research panels for the National Academy of Sciences, National Science Foundation, Office of Naval Research, National Oceanic and Atmospheric Administration and universities and research organizations in the US and internationally and participated in numerous ocean related activities with the U.S. Congress and White House.

Margaret Leinen is the Associate Provost of Marine and Environmental Initiatives and Executive Director of the Harbor Branch Oceanographic Institute, a unit of Florida Atlantic University located in Fort Pierce. She is an internationally known oceanographer, biogeochemist and paleoceanographer and science administrator. Previously, Dr. Leinen is the founder and President of the Climate Response Fund. Dr. Leinen served at the National Science Foundation (NSF) from 2000-2007, as the Assistant Director for Geosciences and Coordinator of Environmental Research and Education where she was responsible for earth, atmosphere, ocean and environmental science. In that position she chaired the US Global Change Research Program from 2000-2001 and was Vice-Chair of its successor, the US Climate Change Science Program from 2002-2007. This program coordinated all US federal climate science investment. During her research career Dr. Leinen served as the Vice-Chair of the International Geosphere-Biosphere Program; member of the US National Research Council Climate Research Committee, member of the Scientific Committee of the Ocean Drilling Program, and in many other national and international positions. Dr. Leinen was the Dean of the Graduate School of Oceanography, the Interim Dean of the College of Environment and Life Sciences, and the Vice-Provost for Marine and Environmental Programs of the University of Rhode Island. Dr. Leinen is a member of the Board of Directors of the American Geophysical Union (AGU), the National Council for Science of the Environment (NCSE) and the National Ecological Observatory Network (NEON, Inc.). She is a Fellow of the American Association for the Advancement of Science (AAAS) and the Geological Society of America (GSA). She is the past Chair of the Atmospheric and Hydrologic Sciences Section of the American Association for the Advancement of Science, and a former President of The Oceanography Society. She received her Ph.D. in oceanography from the University of Rhode Island, her M.Sc. in geological oceanography from Oregon State University and her B.Sc. in geology from the University of Illinois.

Paul Snelgrove is a Professor in the Ocean Sciences Centre and Biology Department at Memorial University, where he holds the Canada Research Chair in Boreal and Cold Ocean Systems. . He is Director of the NSERC Canadian Healthy Oceans Network, a national research network in Canada of ~65 scientists working to develop new tools for sustainable oceans. He recently led the synthesis of the International Census of Marine Life research program, where he was a member of the Scientific Steering Committee. He published the single author book "Discoveries of the Census of Marine Life: Making Ocean Life Count" with Cambridge University Press in 2010. He chairs the international effort to develop a follow-on program to the Census called Life in a Changing Ocean Over the last 25 years he has explored the seafloor with scuba, ships, submersibles and remotely operated vehicles to study the role of transport of larval fish and invertebrates in setting recruitment and biodiversity patterns in marine seafloor organisms. Through this research he has authored over 100 journal articles, book chapters and technical reports, and delivered over 25 invited talks in the last two years including several keynote lectures and a TED Global talk in 2011. He has also been quoted and or interviewed by BBC's World Service and The Forum, NPR, Al Jazeera television, The Los Angeles Times, The Globe and Mail, and Science and Discover magazines. He has served on numerous review panels in Canada, the United States and as a mail reviewer for over 50 different international journals, foundations, agencies, and book publishers. He sits on the editorial boards of Marine Ecology Progress Series, Journal of Experimental Marine Biology and Ecology, Netherlands Journal of Sea Research, Endangered Species Research, and Marine Ecology.

AAAS Staff

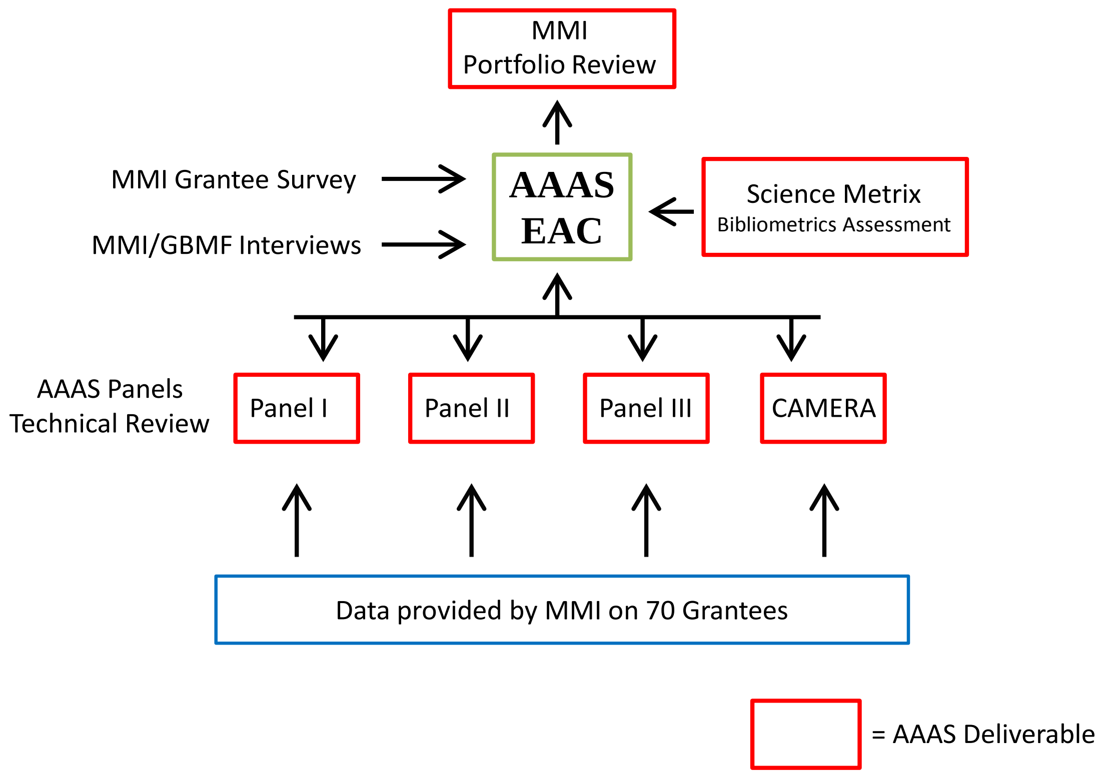
Rieko Yajima is a Project Director with the AAAS RCP where she has led over 35 projects providing clients with technical assistance for improved research, development, and innovation strategies. Her expertise is in evaluating the outcomes and impacts of scientific research as well as planning and implementing programs for strengthening research capacity and competitiveness. She has organized symposia on emerging interdisciplinary topics for the AAAS annual meeting on research collaborations between artists and scientists as well as the science behind delicious food. Trained as a biochemist, Rieko received awards for her Ph.D. research on RNA enzymes and has published over ten research and review articles on the molecular structure and function of protein and RNA enzymes. While completing her Ph.D., she was also a science policy fellow at the National Academy of Sciences in Washington, D.C..

Edward G. Derrick is the Chief Program Director for the AAAS Center of Science, Policy & Society Programs. As director, Dr. Derrick oversees the programs, which combined have a staff of about 40 and an annual budget of over $20 million, and serves as a member of senior management at AAAS. Ed first joined AAAS in 1998 as a member of the AAAS Research Competitiveness Program (RCP). RCP provides review and guidance to the science and innovation community. He became director of the program in January 2004, with responsibility for the development of new business and oversight of all aspects of the design and execution of projects. Ed has participated directly in over 50 RCP projects, having led committees to assist state and institutional planning for research, to review research centers and institutions and to advise state and international funds on major investments. He holds the Ph.D. from the University of Texas at Austin, with a dissertation in theoretical particle physics, and the B.S. from the Massachusetts Institute of Technology, with an undergraduate thesis in biophysics.

Mark Milutinovich serves as Program Director of the Research Competitiveness Program (RCP), part of the Center of Science, Policy, and Society Programs at AAAS. RCP draws upon the resources of the science and engineering community to assist universities, government agencies, research consortia, and other institutions in planning, reviewing or evaluating programs and initiatives in research, development, and innovation. In addition, RCP has extensive experience managing a wide range of proposal review projects, including institutional seed fund competitions, state-wide economic development competitions, and international competitions aimed at building and diversifying research capacity. As Program Director, Mark oversees a staff of seven FTE, with a workload of approximately 30 projects per year. Prior to joining AAAS, Mark completed an internship with the United States House of Representatives Committee on Science after obtaining a Ph.D. in biology from the Johns Hopkins University in Baltimore, Maryland, under the direction of Dr. Doug Koshland. Originally from Ladysmith, Wisconsin, Mark earned a B.S. degree in biochemistry from the University of Wisconsin-Madison.

Daryl E. Chubin is a science advisor to AAAS. He was the founding Director in 2004 of the Center for Advancing Science & Engineering Capacity, at the American Association for the Advancement of Science (www.aaascapacity.org). Prior to that, he was Senior Vice President for Research, Policy & Programs at the National Action Council for Minorities in Engineering after nearly 15 years in federal service. Posts included Senior Policy Officer for the National Science Board; Division Director for Research, Evaluation and Communication at the National Science Foundation; and Assistant Director for Social and Behavioral Sciences (and Education) at the White House Office of Science and Technology Policy. He began his federal career in 1986 at the congressional Office of Technology Assessment (Science, Education, and Transportation Program, until 1993). He has also served on the faculty of four universities, 1972-86, achieving the rank of Professor at the Georgia Institute of Technology. Dr. Chubin is the author of eight books and numerous policy reports and articles on science policy, education policy and evaluation, and careers and workforce development in science and engineering. He is a AAAS Fellow, a Fellow of the Association for Women in Science, a 2006 QEM Giant of Science, a Sigma Xi Distinguished Lecturer 2007-2009, recipient of the Washington Academy of Sciences' 2008 Social and Behavioral Sciences Award, an alumnus or member of three nonprofit boards, an editorial advisor for three journals, a long-time consultant to corporate and philanthropic foundations, a member of various committees of The National Academies, and has been an adjunct professor in the Cornell in Washington Program since 1991.

Appendix II: Overview of AAAS Review Process



AAAS review process of the MMI. The External Advisory Committee (EAC) reviewed the outcomes of Phase I and provided recommendations on Phase II implementation. These findings and recommendations are provided in the report called MMI Portfolio Review. The EAC's review was informed by the following sources: i) a bibliometrics assessment of MMI performed by Science Metrix in order to quantify the impact of the MMI grantees relative to the overall field of marine microbiology; ii) a survey of the MMI grantees; iii) interviews with current and former MMI staff and GBMF scientific advisory board members; and iv) technical assessment of the MMI portfolio by AAAS review panels based on data provided by the MMI. The technical assessment of the 70 MMI awards was performed by four separate AAAS review panels: i) Panel I (21 grantees including GBMF Investigators, summer courses, workshops); ii) Panel II (24 grantees including research infrastructure, biogeochemistry, ecology); iii) Panel III (18 grantees including genomics, bioinformatics), and iv) CAMERA ($25 million database and bioinformatics program). Each of the independent review panels was chaired by an EAC member in order to provide perspective and continuity across the separate review panels.

Appendix III: Experts for the AAAS Review of MMI Program

Removed

Appendix IV: Survey of MMI Grantees

AAAS conducted a survey of MMI grantees to understand how: i) the MMI is influencing marine microbiology research and education; ii) the MMI grant making process is viewed by its awardees; and iii) the MMI program has changed over time

Methodology

The survey was sent to PIs or co-PIs provided by the MMI program office who received grant(s) from 2004-2010. An analysis of the grantee list by AAAS determined that about a quarter of all grantees received more than one grant. To avoid confusion by the grantees, each PI was given only one survey in which they were asked to consider funding from all MMI sources (regardless of the grant type – GMBF Investigator, equipment, tools, or data) when completing this survey.

The web-based survey was distributed through SurveyMonkey. Each individual was given a unique survey link: in the process of completing the survey, the respondent was allowed to go back to an earlier part of the survey and change an answer, but once the survey was complete, no alterations were permitted. A total of two notifications were provided to PIs by the MMI as well as a reminder by AAAS sent two days in advance of the survey closing deadline to individuals who did not complete or did not start the survey.

The survey was sent out to 92 individuals, with 34 responses total (37% response rate). This response rate is lower than expected, given that these PIs would be closely associated with the MMI. It's not clear why the response rate was low though – possible reasons include i) co-PIs not responding because they assumed that the lead PI would answer on behalf of the project team or ii) PIs that are not currently funded (i.e. in 2012) may be less inclined to take the survey. However, the people who did respond were very thorough. The raw data was presented to the EAC, who used their judgement, along with other supplementary material, to harvest the high points. For questions that were designed for an open-ended text response, 'n' refers to the total number of useable responses, which were then identified and categorized in the survey

The survey questionnaire is provided separately as a pdf document.

Appendix V: EAC Meeting Agenda

Monday, June 16, 2012

9:00 am	Review of Process for Day 1 including items to put on the table for discussion)
9:15 am	A. Discussion about the field of marine microbiology Purpose: to set a baseline for the evaluation/outcomes assessment • Based on panel reports I, II, and III Outcome: an EAC-consensus description of the field pre-MMI
10:15 am	B. Discussion about data to incorporate/inform the outcomes assessment Purpose: to ensure that relevant pieces of data get considered for the report • Bibliometrics and social network report • MMI Awardees Survey data • MMI Management and Process: staff interviews, data archive documentation • MMI Grantee List Outcome: have EAC members raise key items that should be brought up later on in the outcomes assessment
11:45 am	Lunch (in meeting room) and discussion of MMI Contributions List Outcome: a general discussion about MMI Contributions mechanism and have EAC comment on whether the funding choices seem appropriate (no proposals to review, based on titles and descriptions in the MMI Grantee Award List; provided in the background materials as an .xls file)
1:00 pm	C. Discussion about the MMI Program Goals Purpose: for the EAC to understand and reflect on the MMI program goals • Based on RFP, staff interviews, AAAS panel reports I, II, and III Outcome: an EAC-analysis of the MMI goals
1:45 pm	D. Integration – Part I: Scientific Questions Addressed Purpose: to synthesize the collective questions that have been addressed by the MMI grantees • Based on panel reports I, II, and III Outcome: a summary to include in the EAC report Include time for an afternoon break
4:00 pm	E. Integration – Part II: People and Community Resources that were enhanced including the MMI Network Purpose: to highlight the major infrastructure that has been enabled by the MMI • Based on panel reports I, II, and III, CAMERA, bibliometrics Outcome: a summary to include in the EAC report
6:00 pm	Break for dinner

Tuesday, July 17th, 2012

8:45 am	Recap or additional time needed to address anything that was missed from Day 1
9:30 am.	F. Integration – Part III: Role and sustainability of CAMERA Purpose: to assess the role of CAMERA in the MMI program and to outline potential paths forward for the MMI to consider • Based on panel reports I, II, and III, CAMERA Outcome: a summary to include in the EAC report
10:30 am	Break
10:45 am	G. Integration – Part IV: MMI Management and Processes and Influence on Program Outcomes, Unique Funding Opportunities for Foundation Purpose: to review funding approaches and alignment with program goals and outcomes • Based on panel reports, MMI staff interviews, data archive analysis, MMI surveys Outcome: a summary to include in the EAC report including recommendations for grant management, review, and impact assessment
12:15 pm	Lunch
1:30 pm	H. Summary: Reflect on Phase I outcomes and solidify recommendation for Phase II Purpose: recap of major outcomes and impacts and use analysis from Phase I to provide recommendation on Phase II implementation; summarize key ideas on how to maximize the program impact (see panel reports) • Based on Day 1 and 2 discussion Outcomes: analysis should include a summary of what has worked well (i.e. what are the successful outcomes or approaches) and what hasn't worked well; recap the main recommendations from the EAC; confirm writing assignments; identify any additional info needed to finish write-up of report