Science-Metrix

EVALUATION OF THE MARINE MICROBIOLOGY INITIATIVE

FINAL REPORT

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Executive summary

Overview

This report presents the results of the Evaluation of the Marine Microbiology Initiative (MMI), prepared for the Measurement, Evaluation and Learning (MEL) Unit of the Moore Foundation. Specifically, Science-Metrix was mandated to provide an external, objective assessment of Phase II of MMI. This report encompasses a brief program profile and evaluation methodology, followed by detailed findings and conclusions on three evaluation themes: (1) initiative design and implementation, (2) initiative achievements, and (3) the potential path forward.

Phase II of the Marine Microbiology Initiative covers the period 2011–2019 and was approved by the Moore Foundation in May 2011. Upon approval of Phase II, MMI's allocation increased by $105 million. MMI's stated overall goal for Phase II is, *"A new paradigm will be established by uncovering the underlying principles that govern inter- and intra-domain microbial interactions and that influence the flow of nutrients in representative marine microbial ecosystems."* To achieve this goal, MMI defined a set of 10 time-phased outcomes to be reached by 2015 and a related set of follow-up outcomes to be reached by 2019.

MMI's key activities toward achieving its goal involve providing research grants for (A) individual investigators who are current and emerging leaders in the field (16 awards); (B) multidisciplinary team research projects that bring disciplines together (21 awards); (C) community resource projects for the creation and sharing of data and the development of tools, methods and infrastructure that are of broad use to the research community (9 awards); and (D) genetic tool development for experimental model systems (EMS), as well as new instrumentation, tools and technology. Note that approach D includes a total of 44 awards, 10 specifically to support the development or purchase of new instrumentation, tools and technology, and 34 awards targeted toward EMS.

MMI also operates according to three defined strategies.

Strategy I: Overcome interdisciplinary barriers that currently hinder scientists from identifying and quantifying nutrients in the ocean, and from understanding how microbes interact with one another and the consequences of those interactions.

Strategy II: Support development of key technologies, tools, methods, computational modeling techniques, and theory needed to advance understanding of microbial interactions and their mediation of biogeochemical cycles.

Strategy III: Increase community adoption of genetics by supporting research to develop experimental model systems, an under-developed, yet powerful way to investigate interactions between organisms and the role of microbes in biogeochemistry.

Methodology

The purpose of this evaluation was to provide (1) an objective assessment of the critical factors that have supported or impeded MMI's achievement of desired outcomes; (2) an analysis of the design and implementation of the initiative's strategies, and associated lessons learned; and (3) an analysis of the "gestalt of risk-taking" across MMI's interventions (level of risk, type of risk taken, and associated lessons learned).

Six lines of evidence were used to collect data for this evaluation: a document and administrative review; bibliometric analysis; an e-survey of principal and co-principal investigators who received an MMI Phase II grant; interviews with internal stakeholders; grantee consultations and site visits; and an expert panel appraisal of MMI's progress toward outcome achievements and future opportunities. Using an evaluation matrix that was validated by the MEL team at the foundation, the evaluation coded and triangulated data from all six lines of evidence with Atlas.ti, a qualitative data analysis software.

A group of five strategic advisors was engaged to provide feedback on selected indicator data collected for each line of evidence and to review the technical reports. The strategic advisors were also called upon for other tasks, including identifying and selecting bibliometric search terms; reviewing the draft survey questionnaire and performing the external pre-test for the e-survey of principal investigators; and reviewing the draft protocol for site visits to grantees.

The evaluation encountered only a few challenges given the generous time frame, adequate budget and collaborative working relationship established with the foundation's MEL team. The first challenge was the absence of an explicit theory of change accompanied by an illustrative logic model that set out the performance expectations of MMI Phase II. The second challenge was the evaluation team's own capacity limitations with respect to assessing progress toward the achievement of scientific outcomes, and the third challenge was the lack of standardized performance measurement data provided to the evaluation in a summary or synoptic format. All three challenges were successfully resolved or mitigated.

Conclusions

The conclusions presented here are grounded in the findings on initiative design and implementation, outcome achievement and the potential path forward for MMI.

Initiative Design and Implementation

> **Conclusion #1: MMI reframed its research focus and goals for Phase II with broad participation from the marine microbiology community. MMI has since adapted its strategies, grant-making approaches and implementation processes in an ongoing and continuous manner. No discernible differences were identified in the relative effectiveness of the strategies, while the multidisciplinary team and investigator award grant-making approaches were determined to be the most effective in achieving expected outcomes.**

The MMI Phase II design and subsequent adjustments were undertaken in close consultation with the marine microbiology community. This resulted in an increased research focus on microbial interactions and nutrient flow, which was well aligned with the 2019 overall goal for the initiative. MMI assumed a leadership role in support of high-risk/high-reward research, such as EMS, with substantial long-term funding to explore emerging research areas and undertake challenges not accessible to most public and private funding organizations. Synergy, interdisciplinarity, and new technologies, techniques, tools and methods were visible across all grant-making approaches and contributed to the overall effectiveness of the portfolio. Multidisciplinary team grants and investigator awards have been the most effective in achieving expected outcomes, while community resources and other tools have been taken up by the marine microbiology community and beyond (e.g., human, terrestrial and plant microbiome fields).

> **Conclusion #2: Two areas were identified with regard to implementation processes that could be improved to address the concerns of the marine microbiology community and to support management decision-making. One is how the relatively small number of MMI grantees is perceived by the marine microbiology community; the other relates to the challenge of establishing a system to assess the performance of basic research.**

MMI management encountered some challenges and made the necessary adjustments in response to technological changes and scientific advancements. Further management attention is still needed to (1) address the perception within the marine microbiology community of exclusivity in the allocation of grants, and (2) develop a more explicit theory of change and standardized performance measurement system.

Outcome Achievement

> **Conclusion #3: Very good to excellent progress has been made toward the achievement of most 2015 and 2019 time-phased outcomes, which portends well for the achievement of the 2019 goal. MMI-funded research has developed new knowledge that has been highly cited, new instruments, tools and data sets have been taken up by the marine microbiology community and promising steps have been taken to develop genetic systems in some single-celled marine organisms. The evaluation has determined that the excellent achievements can be attributed to MMI grant funding, although there were some positive external influences and research management approaches that contributed to the observed outcomes.**

Excellent progress has been made toward the achievement of the 2019 goal to establish a new paradigm by uncovering novel principles about microbial interactions and the transformation of nutrients. There has been an improved understanding of microbial interactions at a single-cell level and organic matter composition and cycling, while progress continues in the areas of theory, synthesis and modeling of biological interactions. The development and utilization of new technologies, techniques, tools, methods and computational models by MMI researchers has been instrumental to these achievements. In addition, MMI has had an unexpected influence on microbial ecology in other environments (e.g., human, terrestrial, plant) and some other areas of biology and ecosystem science. While these outcomes can be strongly attributed to the grant funding itself, the MMI research management approach and external factors have also positively influenced overall outcome achievement.

Potential Path Forward

> **Conclusion #4: Marine microbial ecology has been an accelerating field, in part because of MMI's achievements, and MMI has the opportunity to build on its high tolerance for risk and its strengths in innovative tool and model**

development by pursuing a new five-year goal to further understanding of ecosystem and ocean processes.

The Moore Foundation has an opportunity to build on MMI's successes in advancing the marine microbial ecology field to better understand and model ecosystem and ocean processes in space and time. The challenge will be to integrate new research knowledge developed at all scales of microbial functions from gene to cell level, at the community or consortia level, and at the ecosystem to global level. Much remains to be accomplished to bridge cellular-level data collection, systems biology, computational modeling and theory development. Biogeochemical ecosystem modeling at the microbial community or consortia level holds much promise.

Recommendations

The conclusions of this report led to the following recommendations.

1. That MMI continue the many aspects of its research management approach that have resulted in the outstanding scientific and technical achievements documented in this evaluation study, while elaborating more explicitly how each strategy is expected to contribute to the achievement of outcomes.
2. That MMI develop a more explicit theory of change for its management approach and funded research, including a sequence of expected outcomes, and a standardized performance data collection and analysis system that will allow for the continuous monitoring and periodic in-depth assessment and reporting on expected outcomes.
3. That MMI continue to engage independent expert panels to assess outcome achievement and the path forward, based on their knowledge of the science and MMI data from monitoring and other independent evaluations.
4. That the Moore Foundation continue to support research in marine microbial ecology focused on understanding and modeling the ecosystem at the microbial community or consortia level as recommended by the expert panel.

Table of contents

Tables

Figures

Abbreviations, acronyms and initialisms

ARIF	Average of relative impact factors
CDI	Citation distribution index
DNA	Deoxyribonucleic acid
DOE	Department of Energy
EMS	Experimental Model System Award
EQ	Evaluation question
HCP	Highly cited papers
IF	Impact factor
MEL	Moore Foundation Measurement, Evaluation and Learning Unit
MMI	Marine Microbiology Initiative
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NOAA	National Oceanic and Atmospheric Administration
RC	Relative citation (rate)
NSF	National Science Foundation
PI	Principal investigator
RNA	Ribonucleic acid
TPO	Time-phased outcome

1 Introduction

This report presents the results of the Evaluation of the Marine Microbiology Initiative, prepared for the Gordon and Betty Moore Foundation. Science-Metrix was mandated to provide an external, objective assessment of the Marine Microbiology Initiative, specifically over the Phase II period of 2011–2019. This report encompasses a brief program profile and evaluation methodology, followed by detailed findings, conclusions and recommendations on three evaluation themes: (1) initiative design and implementation, (2) initiative achievements, and (3) the potential path forward.

1.1 Overview of the Marine Microbiology Initiative

Phase II of the Marine Microbiology Initiative (MMI) covers the period 2011–2019 and was approved by the Moore Foundation in May 2011. Upon approval of Phase II, MMI's allocation increased by $105 million. MMI's stated overall goal for Phase II is, *"A new paradigm will be established by uncovering the underlying principles that govern inter- and intra-domain microbial interactions and that influence the flow of nutrients in representative marine microbial ecosystems."* To achieve this goal, MMI defined a set of 10 time-phased outcomes to be reached by 2015 and a related set of follow-up outcomes to be reached by 2019. These outcomes are listed in Appendix E.

MMI's key activities toward achieving its goal involve providing research grants for (A) individual investigators who are current and emerging leaders in the field (16 awards); (B) multidisciplinary team research projects that bring disciplines together (21 awards); (C) community resource projects for the creation and sharing of data and the development of tools, methods and infrastructure that are of broad use to the research community (9 awards); and (D) genetic tool development for experimental model systems (EMS), as well as new instrumentation, tools and technology. Note that approach D includes a total of 44 awards, 10 specifically to support the development or purchase of new instrumentation, tools and technology, and 34 awards targeted toward EMS.

MMI also operates according to three defined strategies.[1]

Strategy I: Overcome interdisciplinary barriers that currently hinder scientists from identifying and quantifying nutrients in the ocean, and from understanding how microbes interact with one another and the consequences of those interactions.

Strategy II: Support development of key technologies, tools, methods, computational modeling techniques, and theory needed to advance understanding of microbial interactions and their mediation of biogeochemical cycles.

Strategy III: Increase community adoption of genetics by supporting research to develop experimental model systems, an under-developed, yet powerful way to investigate interactions between organisms and the role of microbes in biogeochemistry.

A full profile of MMI is included Appendix A.

2 Methodology

2.1 Evaluation objectives and theoretical approach

The purpose of this evaluation was to provide (1) an objective assessment of the critical factors that have supported or impeded MMI's achievement of desired outcomes; (2) an analysis of the design and implementation of the initiative's strategies, and associated lessons learned; and (3) an analysis of the "gestalt of risk-taking" across MMI's interventions (level of risk, type of risk taken, and associated lessons learned).

A list of 11 focal questions to guide the evaluation was developed in conjunction with the Measurement, Evaluation and Learning (MEL) Unit of the Moore Foundation and with MMI representatives. These questions formed the basis of the evaluation matrix (Appendix C). An evaluation matrix is a tool that aligns the focal questions with the measures (indicators) used to inform the findings. Furthermore, it ensures an alignment of the evaluation questions (EQs) and indicators with the lines of evidence and thus reflects how the evaluation is designed to capture the required data to answer the focal questions. This evaluation matrix was reviewed by the foundation's MEL team and MMI, discussed with Science-Metrix during the launch meeting and adjusted during subsequent exchanges.

Science-Metrix aimed to conduct a theory-based evaluation, combining the theory of change[2] and contribution analysis[3] approaches to draw conclusions about whether and how MMI contributed to observed outcomes. A preliminary review of the key documents was conducted by Science-Metrix to build MMI's theory of change for this evaluation. This was depicted visually in a logic model (Appendix D), which illustrated the supposed chain of inputs and events that were expected to lead to outcomes. Contribution analysis then complemented this logic model, articulating internal and external contextual factors that could influence the achievement of outcomes.

2.2 Data collection

Six lines of evidence were used to collect data for this evaluation. These are described briefly below, and a detailed methodology can be found in Appendix B. A group of five strategic advisors was engaged to provide feedback on selected and relevant indicator data collected for each line of evidence and to review the technical reports. The strategic advisors were also called upon for other tasks, including identifying and selecting bibliometric search terms; reviewing the draft survey questionnaire and performing the external pre-test for the e-survey of principal investigators; and reviewing the draft protocol for site visits to grantees. The strategic advisors were selected based on their acknowledged positions as leading experts in the field and the absence of any possible conflict of interest regarding their participation in the evaluation.

Document and administrative review: Content analysis was conducted on 384 documents including internal reviews, administrative data, grantee narrative reports, and relevant peer-reviewed or grey literature.

Bibliometric analysis: The Web of Science bibliographic database of scientific publications was used to build a marine microbiology data set. From this data set, indicators of scientific output and impact were calculated for MMI grantees (see Appendix B for explanations of these indicators).

E-survey of principal investigators (PIs) and co-PIs: The survey solicited primary data from researchers funded under MMI Phase II. The survey population was N=193; of these, 114 respondents completed the survey (n=114). The survey findings are generalizable to the entire population with 95% confidence and a margin of error of ±5.89%.

Internal stakeholder interviews: Six MMI representatives (e.g., program director, program officers and other staff) were interviewed to gather information on the design and implementation of the initiative. Interview data were coded and analyzed according to the evaluation matrix.

Grantee consultations and site visits: Interviews were conducted with 21 principal and co-principal investigators at 12 different organizations; the majority were conducted in person, on-site. Several interviewees were funded under multiple MMI awards. Coverage of all grant-making approaches was ensured with distribution as follows: three community resources awards, seven experimental model system awards (three of which were for the purchase of new instruments and tools), nine investigator awards, and 10 multidisciplinary team research awards.

Expert panel: A panel of seven external experts was convened by the Moore Foundation to appraise MMI progress toward outcomes, achievements and future opportunities. Foundation staff and the chair of the panel worked together to select the other members of the independent international panel. The chair was also one of the five strategic advisors engaged to review the lines of evidence.

2.3 Challenges and limitations

The evaluation encountered only a few challenges given the generous time frame, adequate budget and collaborative working relationship established with the foundation's MEL team. The first challenge was the absence of an explicit theory of change accompanied by an illustrative logic model that set out the performance expectations of MMI Phase II. The evaluation addressed this gap during the evaluation planning phase by developing a logic model and an accompanying theory of change description to assist in orienting the evaluation's assessment of outcomes. Using the theory of change approach helped to minimize the risk that the evaluation would be compromised by misaligned evaluation indicators and data collection tools, or driven by readily available data, or biased by special interest group issues. Another benefit of this approach was that it helped to articulate the assumptions and risks underpinning the theory of change, and in particular helped identify, articulate and assess internal and external contextual factors that could influence the achievement of outcomes—either directly or indirectly and in a positive or negative manner. Consequently, there were no significant limitations to the evaluation findings as a result.

The second challenge was the evaluation team's own capacity limitations with respect to assessing progress toward the achievement of scientific outcomes. Given the specificity of the scientific outcomes, it was decided during the evaluation planning phase that an arm's-length expert panel of researchers in the field would be constituted for the primary purpose of assessing progress toward the

2015 and 2019 time-phased outcomes and 2019 goal statement. The addition of this line of evidence to the evaluation methodology strengthened the independent nature of the outcomes achievement assessment and the credibility of the evaluation as a whole.

The third challenge was the lack of standardized performance measurement data provided to the evaluation in a summary or synoptic format. The evaluation was provided with an Excel spreadsheet containing tombstone data on the grants awarded during Phase II, as well as a set of documents for each of the grants depending on their life cycle status—for example, grant proposals, annual narrative reports and 12 closing reports. Changes in grantee narrative reporting requirements weakly linked to the outcome achievements resulted in inadequate performance measurement data that could not be relied upon. The evaluation had to rely more heavily on the findings of the expert panel in order to mitigate the potential limitations to the assessment of outcomes.

3 Findings – Issue 1: Initiative design and implementation

The discussion on initiative design and implementation covers five themes: MMI relevance (Section 3.1), the role of MMI compared to other funders (Section 3.2), the effectiveness of the initiative's grant-making approaches (Section 3.3) and strategies (Section 3.4), and a discussion of the types of risk taken as MMI progressed (Section 3.5).

3.1 EQ1 In what ways are the initiative's strategies aligned with the current needs of the field?

Finding #1: Strategies were based upon robust analysis of scientific interests and opportunities in consultation with the marine microbiology community. Strategies were continuously adjusted and remained aligned with community interests.

From the outset of Phase II, MMI representatives consulted with the marine microbiology community to gather input on areas of scientific interest to the community. For example, a Request for Ideas was issued by MMI in 2010, whereby the international research community was invited to submit the "best ideas for high impact."[4] As ideas were submitted, common and emerging themes were identified, to help define new research focus areas. Strategies I (overcome interdisciplinary barriers) and II (develop technologies, tools, methods and modeling techniques) were then launched in 2011 to identify the recipients of multidisciplinary team grants and investigator awards (the latter through open competitions).[5] Again in 2014, expressions of interest were solicited from the international scientific community to develop experimental model systems for marine protists.[6] Moreover, consultations with thought leaders helped define the 2019 MMI long-term outcome and identify potential grants to be funded under Phase II.[7] Internal interviewees also described multiple avenues that were taken to determine the needs of the community, including seeking expert advice to complement internal brainstorming, active staff searches for new ideas, informal surveys, visits to other funders, and opinion-generating workshops with researchers active in the field.[8] Most survey respondents (88%; n=99) said that MMI Phase II grants were addressing important needs of the marine microbial ecology community.[9]

It is also evident that the Moore Foundation was flexible, refocusing its investments on strategies as needs emerged or became less prevalent. Adjustments were made based on internal review and gap analysis. Three key examples are described below.

- Between 2004 and 2015, the subfield of molecular ecology was the fastest growing topic in marine microbiology in both the United States and in the world. This was also a main area of specialization for MMI Phase I papers, demonstrating that the initial MMI emphasis on molecular ecology at that time closely aligned with global research trends.[10] At the end of MMI Phase I, a "reframe" process took place to strategically position Phase II. This reframe modified the MMI objectives, taking into consideration progress made against Phase I outcomes and general advances made in the field.[11]

- An internal strategic review of MMI, conducted in 2013, revealed that (1) substantial grant investments had already been made toward Strategy I; (2) there were gaps and opportunities for further funding Strategy II; and (3) despite "high potential for transforming the field," Strategy III had not yet been launched. Another allocation request was thus submitted to the Board of Trustees in January 2014 for an additional $30 million to address the gaps and opportunities within Strategy II and to launch Strategy III.[12]
- Following a 2015 internal strategic review, a decision was made to end support for bioinformatics platforms as they were "unable to respond to rapidly evolving DNA sequencing technologies and analysis tools."[13] Nevertheless, MMI-supported papers continued to specialize in bioinformatics as this is a rapidly growing research area (ranking in the top 10% in terms of growth at the US and world levels).[14]

Finding #2: Having contributed significantly to the growth of the molecular ecology field (Phase I), MMI evolved to specialize in community and trophic ecology, which was aligned with an appropriate yet ambitious overarching goal (i.e., to establish a new paradigm by uncovering novel principles about microbial interactions and nutrient flow).

Not only did MMI respond to needs of the research community in marine microbiology, it also helped to shape the field. While MMI's Phase I output in the topic of molecular ecology accounted for 10% of the total US output in this phase, it also accounted for 14% of the overall US growth in publication output in this topic. MMI-supported publications thus had a major effect on growth in this topic.[15] Grantees also said that Phase I funding enabled access to novel molecular technologies and instruments that were critical in generating new fundamental knowledge to catalyze the Phase II research.[16]

For Phase II, the bibliometric analysis found that MMI-supported publications shifted from being specialized in molecular ecology to specializing in the topic of community and trophic ecology. This new focus is well aligned with the 2019 goal for Phase II (i.e., microbial interactions and nutrient flow). Further, the expert panel cited many examples of how the field has evolved since 2011. For example, "fluorescence-activated cell sorting enables microbiologists to sort mixtures of cells, one cell at a time," "intensive field studies in microbial ecology have made great strides across a breadth of different habitats, including once difficult-to-access environments such as the deep-sea floor and the sediments beneath it," and "understanding of the diversity and function of viruses in the oceans has mushroomed, requiring us to think in new ways about ecology and evolution in the marine realm."[17] Given these advancements, the panel expected "significant progress towards excellence" in all the 2019 MMI goals, but recognized "not all can be fully achieved by 2019 given their ambitious nature." Specifically, the panel characterized some MMI expected outcomes as "stretch goals"—that is, objectives that are challenging but that continue to provide important guidance to researchers in an accelerating field.[18] Outcome achievement is discussed fully under Section 4.1.

3.2 EQ2 What is the role of MMI in supporting this field in relation to government and other private funders?

Finding #3: MMI has assumed the role of supporting high-risk research that government funders will not otherwise support without the necessary preliminary data. MMI has played a leadership role among private funders and has facilitated the sharing of research platforms and resources.

Philanthropic organizations are uniquely placed to fund scientific research as they are not limited by the same constraints that public funding imposes. MMI internal interviewees said that MMI has taken advantage of this position, always wanting to fund research where MMI can make a difference, "to fund things that others are not funding." For example, if MMI staff members confirm that a researcher is bringing a method into the field for the first time, they would be interested in supporting this work because government funders would normally not do so, due to the lack of preliminary data. Internal interviewees said that MMI "can take that leap of faith."[19] Internal documents are even more explicit as the grant development instructions for funding applicants state that MMI aims to "fund components of research program that are unlikely to be funded elsewhere"; the goal is "not to supplant other sources of support to [their] lab, but rather to complement other sources of support and enable research that would otherwise not be funded by others."[20]

Almost all interviewed grantees confirmed that once their MMI projects generated preliminary data or demonstrated the feasibility of the technologies, techniques, tools and methods, they then successfully leveraged their achievements to obtain ongoing funding from a variety of government agencies.[21] More widely, most survey respondents (85%; n=101) reported that their MMI project was higher risk than their other research projects funded by other sources, and 78% (n=92) said they applied for additional funding from a variety of sources to continue the work of their MMI-funded project.[22,23] This willingness to take risks where public funders will not was summed up by the expert panel as follows.

> Private organizations generally seek mechanisms to support science that do not duplicate government efforts, by taking advantage of their independence and associated flexibility to maximize impact. In this sense, the Moore [Foundation] has prioritized the promotion of higher risk science that promises high reward. Their independence has allowed them to develop an integrative and visionary program that publicly funded programs typically cannot; the latter often fund a series of largely unrelated projects of shorter term (e.g., 3-year maximum) and with little potential for the whole to exceed the sum of its parts.[24]

Leadership and complementarity

Several major public and private funders invest in marine microbiology research globally. In terms of publication output, the public players who support the most research in the US include the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE) and the National Institutes of Health (NIH), in that order (Table 1). Among all funders, the Moore Foundation stands out as the largest[25] private funder of research in marine microbiology. In fact, it is the only private funder ranking among the top 20 funders in the field, which is composed mainly of large governmental organizations. The next largest private contributor (the David and Lucile Packard Foundation) produced close to five times fewer papers than the Moore Foundation over the 2009–2016 period.[26] Furthermore, MMI Phase II ranked first, or very close to the top, among private and government funders across all scientific impact indicators (Table 1).[27] The scale of the foundation's and of MMI's contribution to research output in marine microbiology, relative to other funders, demonstrates their pivotal role in supporting the production of a notable volume of new, highly cited knowledge in this field.[28]

Table 1 Scientific output and performance of the top 20 government and top 10 private funders of marine microbiology research (2009–2016)

		Output	Impact		
Funding Agency	Country	Papers	ARIF	$HCP_{10\%}$	CDI
Government					
Nat'l Sci. Foundation (US-NSF)	**USA**	**6,361**	**1.31**	**19.3%**	**14.6**
European Commission	EUR	4,654	1.18	14.7%	11.4
Nat'l Natural Sci. Foundation of China (NSFC)	CHN	4,053	0.86	8.5%	-3.4
German Research Foundation (DFG)	DEU	1,962	1.24	16.6%	12.5
Chinese Min. of Sci. and Tech. (MoST)	CHN	1,787	0.83	10.4%	-3.3
Nat'l Oceanic and Atmospheric Administration (NOAA)	**USA**	**1,768**	**1.16**	**15.3%**	**10.6**
Natural Environment Research Council (NERC)	GBR	1,584	1.38	20.4%	14.7
Nat'l Aeronautics and Space Administration (NASA)	**USA**	**1,430**	**1.30**	**20.4%**	**15.2**
Natural Sci. and Eng. Research Council of Canada (NSERC)	CAN	1,314	1.20	14.0%	9.7
Chinese Academy of Sci. (CAS)	CHN	1,093	0.87	9.4%	-3.2
Nat'l Center for Sci. Research (CNRS)	FRA	1,062	1.19	10.7%	8.1
Japan Society for the Promotion of Sci. (JSPS)	JPN	975	1.01	5.6%	-3.9
Nat'l Agency for Research (ANR)	FRA	930	1.24	13.3%	12.2
US Department of Energy (DOE)	**USA**	**911**	**1.33**	**21.6%**	**14.5**
Nat'l Institute of Health (NIH)	**USA**	**898**	**1.18**	**12.3%**	**7.4**
Australian Research Council (ARC)	AUS	835	1.26	17.8%	14.1
Nat'l Council for Sci. and Tech. Development (CNPq)	BRA	748	0.85	6.1%	-3.1
Min. of Education, Culture, Sports, Sci. and Tech. (MEXT)	JPN	730	0.98	4.8%	-7.6
Research Council of Norway (RCN)	NOR	667	1.11	12.2%	10.7
Russian Foundation for Basic Research (RFBR)	RUS	571	0.50	1.7%	-22.4
Private					
Gordon and Betty Moore Foundation	**USA**	**820**	**1.56**	**28.9%**	**22.5**
MMI Phase II	**USA**	**222**	**1.81**	**22.7%**	**18.8**
David and Lucile Packard Foundation	USA	166	1.40	20.9%	15.5
Leverhulme Trust	GBR	136	1.43	24.0%	20.4
Alfred P. Sloan Foundation	USA	109	1.27	31.4%	15.9
Agouron Institute	USA	107	1.56	32.9%	23.9
Carlsberg Foundation	DNK	90	1.21	16.7%	15.4
Knut and Alice Wallenberg Foundation	SWE	75	1.30	25.5%	20.6
Tula Foundation	CAN	72	1.34	19.6%	15.1
Walter and Andree de Nottbeck Foundation	FIN	71	1.04	10.2%	4.5
Andrew W. Mellon Foundation	USA	59	1.43	10.4%	8.4

Note: Coloring for averages and indices ranges from red (lowest score, below average or index) through white (on par with index) to green (highest score, above average or index).
Source: Computed by Science-Metrix using the Web of Science database (Clarivate Analytics)

MMI and other funders often play complementary roles, using different funding approaches and focusing on different research areas. While government bodies tend to fund a broad array of research topics, MMI targets science opportunities that contribute to the achievement of its time-phased and long-term outcomes.[29] In fact, this appears to hold true for most private investors because the bibliometric analysis found that the specialization pattern of private funders was more polarized than that of the larger government funders. In other words, while public funders more evenly support research across all areas, the smaller private funders adopt clearer strategies regarding the type of research they fund, which resulted in more extreme scores in the specialization index across areas.[30] To illustrate, analyses at both the topic and subfield level were conducted as part of the bibliometric co-word analysis.[31]

- In the topic of community and trophic ecology (a main focus for MMI Phase II), MMI has the highest specialization index. The only other private funders showing strong specialization in this topic are the Walter and Andree de Nottbeck Foundation, the Carlsberg Foundation, the Andrew W. Mellon Foundation and the David and Lucile Packard Foundation. Looking at output, the total number of papers funded by these private foundations together still only equates to 60% of the total of Moore Foundation-supported papers. Among the larger government funders, only one is nearly as specialized as MMI Phase II in community and trophic ecology, namely NASA.[32]
- With regard to subfields, again the Moore Foundation ranked as one of the most specialized and largest funders of research on microbe–microbe interactions and nutrient flow. None of the other private funders contributed a comparable number of publications on microbe–microbe interactions and nutrient flow, and their specialization scores were lower. For public funders, only the NSF and the European Commission supported more research papers on microbe–microbe interactions than the Moore Foundation.[33]

Thus, despite some overlap between funders, the Moore Foundation is making a unique and important contribution that is not matched by any other private foundations.

The internal interview data indicate that MMI staff members do landscape analyses to see what others are funding, or are interested in funding, so that agreements can sometimes be made to share the cost and use of expensive research equipment and avoid duplication. MMI staff members also look for areas of complementarity where funding, resources or research platforms may be leveraged with other types of organizations.[34] One example of this is the NSF funding to build CLIO, an underwater autonomous vehicle that serves as a sampling machine for DNA, gene expression and biogeochemical analysis. Central to obtaining the NSF grant to build CLIO was an MMI investigator award that funded the scoping and sampling methods used by this machine and the instrumentation inside it that makes it work.[35] Funding from the Simons Foundation was also cited repeatedly in the interview data as providing grantees with an opportunity to undertake research that was complementary to and synergistic with their MMI projects. Of note is a five-year project involving two MMI investigator award recipients to model a marine microbial ecosystem, basin-wide, integrating microbial interaction models, physics and chemistry in basic biology data. Several other examples of complementarity were also cited in the interview data—for example, obtaining ship time through collaborative networks with the Simons Foundation, the University of Hawaii, the Schmidt Ocean Institute and the US Navy, as well as the sharing of laboratory equipment and instruments (such as a mass spectrometer, a flow cytometer) and the use of remotely operated vehicles for data sampling and analysis.[36]

3.3 EQ3 How effective have MMI's grant-making approaches been relative to one another?

Finding #4: Multidisciplinary team grants and investigator awards have been the most effective in the achievement of expected outcomes. Community resource tools have been used by researchers in over 100 countries, while half of the MMI researchers who had used Phase II community resource tools found them to be either very or extremely useful. It is too soon to qualify the effectiveness of the EMS approach, which only began in 2015. Non-EMS instruments, technologies and tool awards, which have cut across all grant-making approaches, have been effective and contributed to the overall achievement of outcomes.

Under Phase II, 90 grants were allocated for a total of $79,467,036 (initial budget). The largest number of grants was awarded under the experimental model systems approach, encompassing 44 grants in total. Note that 10 of these 44 were specifically for the purchase or development of new instruments, technologies or tools and are not targeted toward developing EMS per se. A total of 21 multidisciplinary team grants were awarded, as well as 16 investigator awards and 9 community resources grants. In terms of the distribution of grants by funding amount, the multidisciplinary team grants ($30,390,729) and the investigator awards ($29,789,000) received the highest overall amounts of funding. Experimental model systems received $15,710,424, and community resources grants received $3,576,883.

The number of grants is not reflective of the amount of the investment of each grant-making approach. This means the average grant amount varies considerably from one grant-making approach to the other, ranging from $357,055 for experimental model systems to $1,861,813 for the investigator awards.[37]

Multidisciplinary team grants and investigator awards

Given that multidisciplinary team grants and investigator awards account for most of the funding and that EMS grants were only awarded in 2015, it may seem obvious that the foundation's 2015 internal strategic review of the initiative found that success in generating breakthroughs drew heavily from the former two award types.[38] However, because the review did not specify the methodology used to assess the 2012–2015 outcomes, and because it mainly represented the MMI internal perspective, this finding was externally confirmed by two lines of evaluation evidence. First, an analysis of the grants database found that multidisciplinary team grants and investigator awards were the predominant contributors to the logic model outcomes (refer to Table 5 in Appendix F for details). Second, the expert panel also mapped most achievement of the time-phased outcomes (TPOs) to the multidisciplinary team grants, followed by the investigator awards (see Table 6 in Appendix F for mapping). In particular, the panel said that the investigator awards have improved the "capacity of the field to address the link between microbial identities, functions, and their environmental distribution," while the multidisciplinary team grants provided "an important and timely addition to the MMI that are advancing the field with potential for considerable impact."[39]

Aside from the large monetary investment, several explanations for this effect are plausible. For example, it may be that the multidisciplinary team and investigator awards approaches have certain advantageous characteristics over the community resources or EMS approaches. Grantees funded under the former two approaches said they had a great amount of autonomy, which encouraged creative research and the application of unproven innovative technologies, techniques, tools and methods. There was considerably less principal investigator autonomy reported for community resource and EMS awards because of the well-defined deliverables and timelines, and the more frequent oversight and monitoring activities by MMI staff. This was viewed as normal by the grantees given the more deliverables-based projects being funded under those award types. The longer-term funding duration of the investigator awards, and to a certain degree the multidisciplinary team grants, was also considered important by the principal investigators in attracting and retaining highly qualified professional resources to work in their labs (i.e., postdoctoral and doctoral students, skilled technicians), undertaking long-term methods development research, and managing a research portfolio with an acceptable level of calculated risk.[40] These sentiments were also reflected by the expert panel who said, "the Foundation's ability to take risks, make long-term and relatively large commitments and fund interdisciplinary teams of scientists allows it to undertake challenges not accessible to most other science funding organizations."[41]

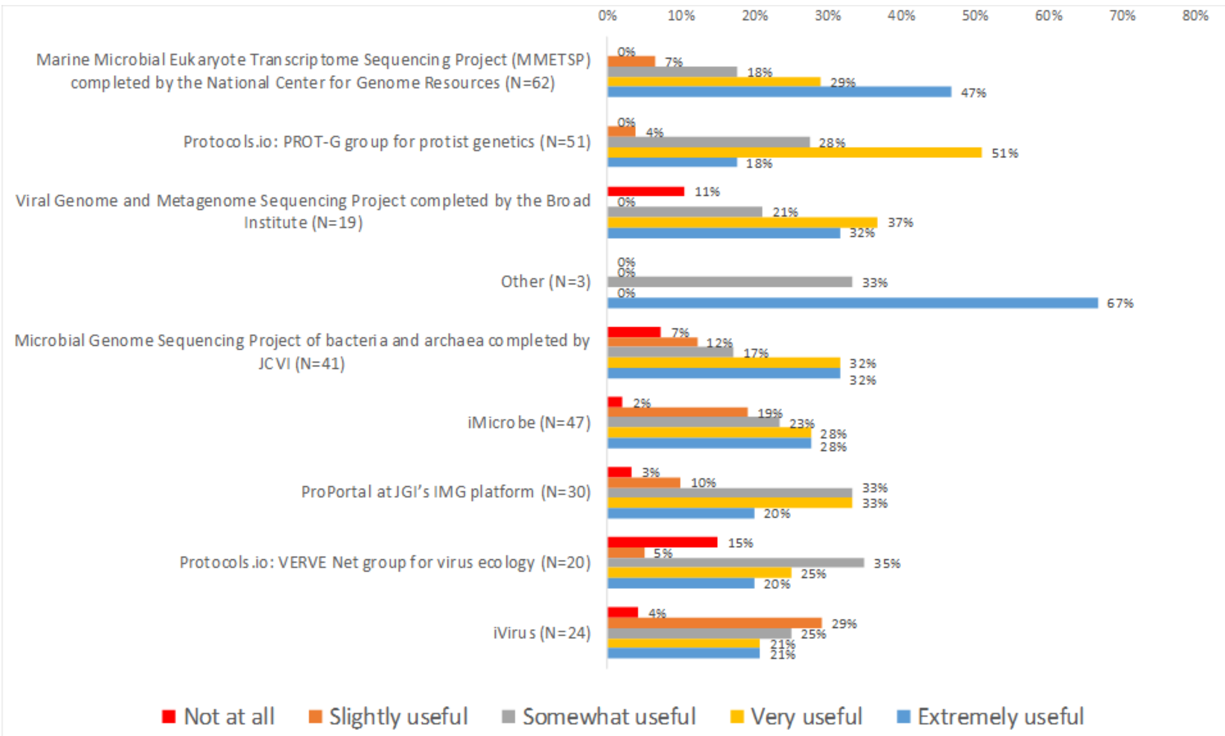
Finally, there is some anecdotal evidence that the selection process for the multidisciplinary team grants and investigator awards may also have influenced success. Grantees describe the process as follows. In 2010, MMI issued a public Request for Ideas that enabled the creation of the Phase II 2019 goal statement and subsequently helped identify multidisciplinary team research projects that aligned with that goal. The idea summaries went through a screening process, and a subset of proponents were asked to submit full proposals. These were subsequently reviewed by MMI staff to make suggestions for improvements and then revised by the proponents until their proposals were accepted. In 2012, MMI issued a public call for investigator award proposals with well-defined selection criteria that aligned with the Phase II 2019 goal statement.[42] The rigorous honing process for multidisciplinary team grants and the use of goal-aligned selection criteria for investigator awards likely ensured that selected projects were already set up for success and were closely aligned with the expected outcomes from the outset.

Community resource projects

Although not as effective as the two grant-making approaches discussed above for outcome achievement, the community resource grant-making approach has yielded success in another way. Bibliometric analysis found that the Phase I community resource outputs (e.g., bioinformatics tools, web platforms, analytical tools, sequencing data) have reached a large audience, even outside the core of marine microbiology. Researchers from over 100 countries referenced a community resource project output at least once. US institutions represented over one third of the 25 institutions that most frequently referenced community resource project outputs, followed by institutions from France and Germany (12% each). Furthermore, nearly 80% of papers referencing community resource project outputs fall in the periphery of marine microbiology, indicating that MMI's community resources are reaching out broadly to researchers who are not at the core of the field supported by MMI.[43]

While the bibliometric analysis concluded that it was too early to document the uptake of Phase II community resource projects by the broader marine microbiology community, survey data can fill some of that gap for a subset. About half of the MMI researchers who used community resource tools between 2011 and 2017 (funded in either Phase I or II) found them to be either very or extremely useful. The Marine Microbial Eukaryote Transcriptome Sequencing Project (MMETSP) (which was strategically a part of Phase I but occurred during Phase II activities), the Protist Research to Optimize Tools in Genetics (PROT-G) project and the iMicrobe tool were the most frequently used resources according to survey respondents (see Figure 1).

Figure 1 Survey question: How useful to your research have the MMI community resources been between 2011 and 2017?



Source: Compiled by Science-Metrix using MMI e-survey data[44]

Experimental model systems

The effectiveness of this grant-making approach cannot be fully assessed as it was only launched in 2015.[45] What can be said so far is that this approach (specifically the 34 funded EMS projects) has contributed primarily to progress toward the 2019 TPO 2, "Experimental model systems for probing microbe–microbe interactions and nutrient flow enable generation of new ecological and evolutionary hypotheses for ocean investigation" (see expert panel assessment, Table 6), and that the EMS approach typifies purposive risk-taking (discussed under Section 3.5). The other grants for new instruments, technologies and tools awarded for the most part in late 2016 could not be fully assessed either, given the short time frame, although a few principal investigators interviewed during the stakeholder site visits found them to be a valuable complement to their ongoing MMI research.

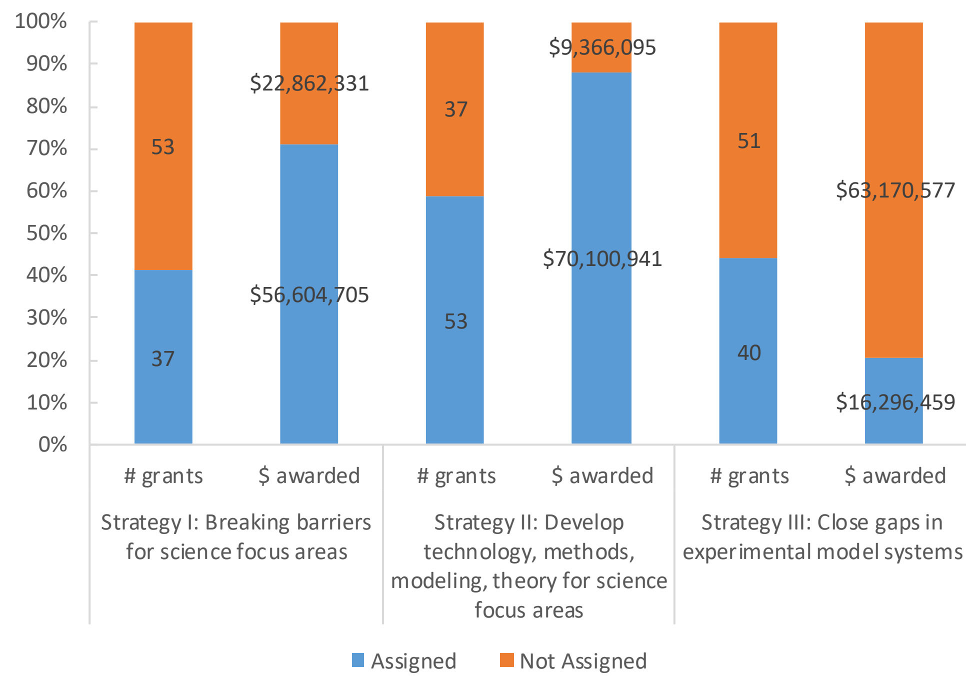
3.4 EQ4 How effective have MMI's strategies been relative to one another?

Finding #5: It was not possible to determine the relative effectiveness of each individual strategy because program actions addressed them simultaneously. Interdisciplinarity and new technologies, tools and methods were visible across all grant-making approaches and contributed to the effectiveness of the portfolio, whereby the sum was greater than the parts.

To give context to this section, recall that the MMI operates according to three defined strategies (described in Section 1.1). Briefly, Strategy I aims to overcome interdisciplinary barriers, Strategy II supports development of technologies, tools, methods and modeling techniques, and Strategy III seeks to develop experimental model systems.

Figure 2 presents the distribution of the grants by strategy and the corresponding awarded amount. Out of the 90 grants awarded by MMI, 37 addressed Strategy I (with a corresponding amount of $56.6M), 53 addressed Strategy II (with a corresponding amount of $70.1M) and 40 addressed Strategy III (with a corresponding amount of $16.3M).[46] Note that grants could be assigned to more than one strategy.

Figure 2 Distribution of grants assigned to each strategy and grant funding



Note: Some grants were assigned to several strategies.
Source: Compiled by Science-Metrix using the MMI Phase I and II grants database

Interviewed grantees said there were successes to be found among all three strategies individually, as follows.

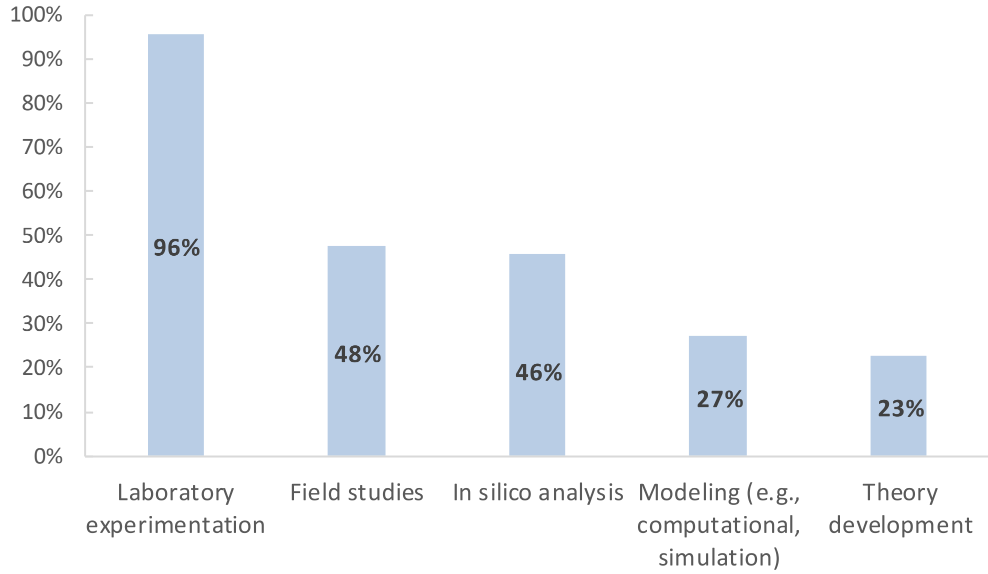
- Strategy I: MMI's encouragement of interdisciplinary research as a strategy cut across all grant-making approaches, with only a few exceptions of individual investigators who did not have formal collaborations with co-principal investigators. Even in these cases, it was noted that the composition of the laboratory staff can also be quite interdisciplinary. The bringing together of diverse disciplines to move the field forward faster was evident in the interview data, not only through collaborations between chemists and microbiologists, which were central to the field, but also through collaborations between researchers with expertise in cellular biophysics, bioinformatics, biogeochemical modeling, synthetic and quantitative genetics, and engineering.[47]

- Strategy II: Grantees combined lab, field and in silico work to develop new methods and techniques for various scientific instruments (e.g., mass spectrometer, atomic force microscope, environmental sample processor) that have increased the pace of scientific discoveries and amount of available data. Some community resource projects have then made the research methods, protocols and database tools available for wider use (e.g., protocols.io for protist genetics, or other microbe-specific data sets).[48]
- Strategy III: MMI has funded projects that are experimenting with organisms from a wide range of marine protist taxonomic groups, such as diatoms and dinoflagellates. While stable transfection and the creation of genetic mutants has occurred in some cases, it has reportedly remained elusive for most project teams at the time of the evaluation. Nevertheless, progress is ongoing and there was considerable grantee optimism expressed as to the potential for the EMS grants.[49]

But more importantly, a grant is often a blend of strategies, and the use of interdisciplinary teams, experiences and methods within a single project is encouraged, according to MMI internal interviewees. MMI staff members also suggested that the grant-making approaches are tactical and serve to support the strategies. While Strategy III is clearly distinguishable from the others, staff acknowledged that it is not always clear which of the other two strategies is the primary emphasis of a grant.[50] Survey responses further confirm this, showing a clear overlap across Strategy I (interdisciplinarity) and Strategy II (new technology, tools, methods).

- Most survey respondents reported that new and/or strengthened collaborations brought new expertise (84%; n=97) and tools or techniques (75%; n=87) to their research.[51]
    - More specifically, a majority of respondents with a multidisciplinary award (71%; excluding grantees with more than one type of grant) reported that collaboration brought new tools or techniques, demonstrating how that grant-making approach supports Strategy II.
- Respondents whose team included more than one researcher reported that their team included members coming from different disciplines (63%; n=66), members who were multidisciplinary in nature (59%; n=62) and that knowledge produced by the team was based on insights from several disciplines (57%; n=60).[52]
    - More specifically, a majority of respondents with a multidisciplinary award (71%; excluding grantees with more than one type of grant) reported that collaboration brought new tools or techniques, demonstrating how that grant-making approach supports Strategy II.
- Most respondents reported using at least two different research approaches (e.g., including but not limited to laboratory experimentation and field studies) in their work (
Figure 3).[53]

Figure 3 Survey question: Which of the following approaches are used in your project? (N-118)



Source: Compiled by Science-Metrix using MMI e-survey data[54]

The cross-pollination of the various strategies and grant-making approaches then contributed to an effect where the sum (progress toward TPO achievement) is greater than the parts (any one individual strategy). Indeed, interviewees said that the mix of undirected research along with awards targeted toward specific TPOs creates a "holistic approach"—for example, where improved tools allow for new questions to be asked.[55] Similarly, the expert panel said,

> Overall progress has been enabled by the synergy from the suite of different funding mechanisms including block funding to exemplary PIs, multidisciplinary projects and tool and method development, both more dynamic to solve current needs, and community resources, together providing for more [than] the sum of the parts.[56]

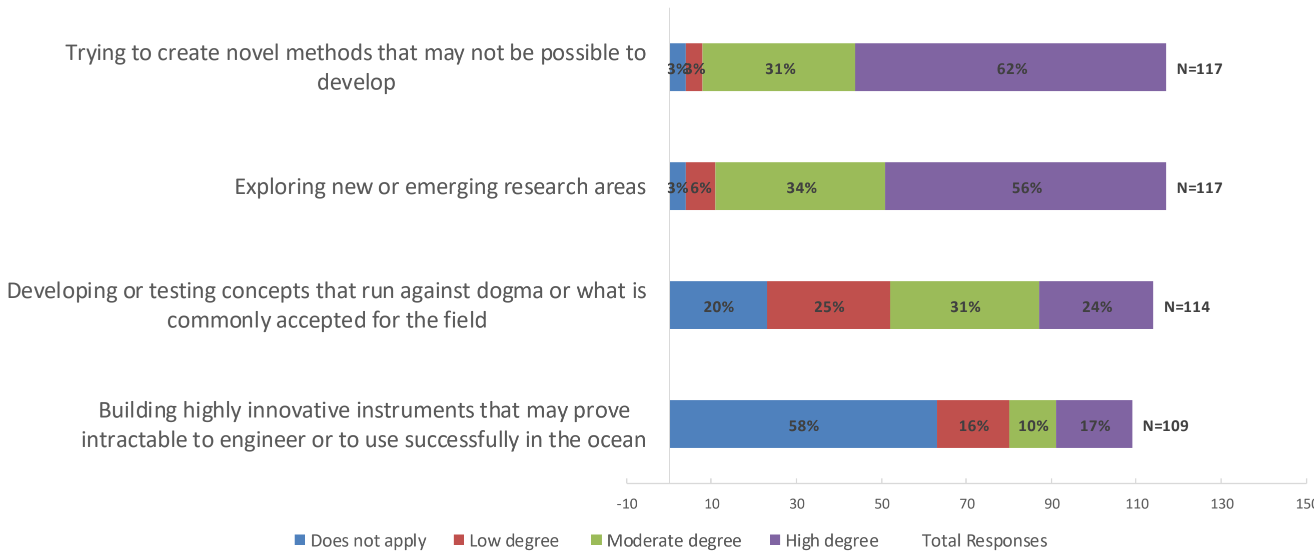
3.5 EQ5 What types of risk (structure of science, conceptual, methods, technology) has MMI taken in its interventions? How could MMI consider risk in potential future interventions?

Finding #6: MMI exhibited a high degree of risk tolerance related to creating novel methods, exploring emerging research areas, testing concepts and building innovative technologies. Various risk mitigation strategies were employed to lower the degree of risk and to address challenges associated with interdisciplinarity, building individual research careers, and balancing research autonomy with successful outcome achievement.

While a certain level of risk is inherent to all scientific research, planned risk-taking can often drive innovation and development.[57] As demonstrated earlier (see Finding #3), MMI has embodied this concept, purposely funding high-risk endeavors, filling a niche that other funders do not. In this respect, internal interviewees said that MMI wants to be a catalyst that positions grantees to get downstream funds.[58] This was confirmed by the majority of survey respondents (70%; n=57) who reported that, unlike MMI, other funding agencies, including US federal sources and international funders, would not support projects at high risk of failure. When asked to explain why, respondents said that other funders first require preliminary results or demonstration of feasibility.[59]

Having established that MMI is risk-tolerant, the discussion now turns to the types of risk that MMI is taking. As shown in Figure 4, survey respondents primarily described their MMI project as trying to create novel methods that may not be possible to develop (62% "high degree"; n=73) and exploring new or emerging areas (56% "high degree"; n=66). About half of the respondents also said their projects addressed conceptual risk to some degree (31% "moderate degree", 24% "high degree").

Figure 4 Survey question: To what degree do the following statements describing high-risk research apply to your MMI project?



Source: Compiled by Science-Metrix using MMI e-survey data[60]

In more detail, a commonly cited example of purposive risk-taking were the experimental model systems grants, which encompasses at least two types of risk: novel methods and emerging research areas. Internal interviewees said that MMI is trying to tap into the leading edge of current technology where recent breakthroughs—such as the CRISPR gene editing technology—make the EMS approach worth attempting in spite of the risk. Multiple interviewees stated that the pay off if successful would be large, so long as the new model systems are taken up by the scientific community, likely requiring a culture shift.[61]

The expert panel also highlighted EMS grants as a "significant example of a high risk/high reward project that has the potential to develop significant new understanding in marine microbial ecology."[62] It was said that this was a particularly ambitious aspect of TPO 2 because classical genetic approaches can be applied to very few single-cell eukaryotes. As described by the panel,

> *Chlamydomonas* is the archetypal model organism, in which it has been possible to isolate mutants for decades; this has led to a vast literature of molecular genetic studies. However, equivalent progress has

> not happened with marine single cell eukaryotes, which lack tractable genetic systems. The EMS initiative was very high risk because it was not known if genetic systems could be developed in any of these marine organisms. Nevertheless, the ability to genetically manipulate these systems would be a major step forward and yield very high reward. To date very promising progress has been made for diatoms, a choanoflagellate, two ciliates, and the protalveolate *Perkinsus*.[63]

Being risk-tolerant does not exclude the need for risk management, ensuring that the effects of the risks taken are either eliminated or reduced to an acceptable level.[64] MMI used several informal strategies to mitigate its numerous risks. For example, according to grantees, the large number (34) of EMS projects funded and the short amount of time allowed to achieve the first step of genetic transfection was a risk mitigation strategy—that is, distributing risk broadly and supporting projects just for a limited time. But some of the principal investigators felt that the time allotted to develop, demonstrate and optimize transfection protocols was too short as they also struggled with diminishing resources and uncertain prospects for ongoing funding. To address some of these concerns, the Moore Foundation has provided an additional $4.5 million to the most successful of the EMS projects since the interviews were conducted.[65] To further lower the risk, MMI staff spoke with the NSF to clarify that MMI intended to provide only limited funding for follow-on EMS projects.[66] Some other examples of risk mitigation are described below.

- The investigator awards approach had a built-in risk mitigation strategy in that the selected awardees were already very accomplished, with some very high-profile publications in highly ranked peer-reviewed journals and with established track records of success. These PIs were conscious of taking calculated risks without jeopardizing their reputation and the careers of their postdoctoral and doctoral students. In this regard, MMI also advised some principal investigators not to assign their students to only high-risk research projects and to ensure a balance in the research portfolio. In fact, maintaining a balanced portfolio of high-, moderate- and low-risk research projects appeared to be the risk mitigation strategy of choice for most principal investigators across award types.[67]
- The multidisciplinary team awards also contain a certain amount of inherent risk as the team composition—including each member's scientific discipline, scientific agenda, location and interpersonal familiarity—can be challenging to present as one unified vision. The interviewees said that the key to creating a productive working relationship was to find the mutual interest in demonstrating how microbial interactions matter in the understanding of nutrient flow in the oceans. Multidisciplinary team risk was also somewhat mitigated by MMI funding for in-person team meetings, to build upon any collaboration history and encourage future partnerships among the members.[68,69]

Looking toward the future, internal stakeholders expressed concern that MMI may not be taking enough risk. They were concerned that there may be a cultural norm among staff and grantees that only successes are expected, without the necessary failures that often come along with high-risk endeavors. Internal interviewees indicated there was no guidance in research management literature on how to measure risk and relative risk, or on what percentage of failure would be acceptable for an institution such as the Moore Foundation. That said, there is evidence that MMI does take more risks than many other research organizations and has clear policy and processes in place to encourage risk-taking by grantees.

4 Findings – Issue 2: Achievement of outcomes

Issue 2 begins with an assessment of outcome achievement, through the lens of both the time-phased outcomes and MMI's theory of change (Section 4.1). This is followed by an examination of MMI's contribution to the results observed thus far (Section 4.2). Findings on unintended consequences (Section 4.3), challenges and adaptations (Section 4.4) round out the discussion.

4.1 EQ6 In what ways are the initiative-level scientific and technical outcomes being achieved? In what ways are the strategy-level outcomes being achieved?

Finding #7: Laboratory and field investigations have led to excellent progress in understanding microbial interactions at a single-cell level, evolutionary hypotheses, organic matter composition and cycling, as well as ecosystem processes. MMI played a significant role in the advancement of marine microbial ecology as an emerging field of study. Excellent progress has been made toward establishing a new paradigm by uncovering novel principles about microbial interactions and nutrient flow.

Regarding initiative-level and strategy-level achievements, MMI was working toward TPOs to be reached by 2015 and 2019 (Appendix E). Progress toward the 2019 goals was assessed by the expert panel. The panel scored progress as excellent for three of the goals, one very good-to-excellent, two very good and two good (Figure 5). The highlights of this ranking are provided after the figure, but the reader is encouraged to refer to the full expert panel report for details.

Figure 5 Expert panel rating of MMI 2019 time-phased outcomes (TPOs)

2019 Time Phased Outcomes			Level of Progress
Goal 1 Demonstrate importance of microbial interactions in ecosystem processes	**Goal 2** Enable new evolutionary hypotheses via EMS	**Goal 4** Single-cell level mechanistic understanding of microbial interactions & nutrient flow	**Excellent**
Goal 10 Understand organic matter cycling by integrating organic matter composition and microbial analyses			**Very good to excellent**
Goal 3 Computational models accommodate the complexity of microbial interactions and nutrient flow in the ocean	**Goal 5** Investigations of geochemical pathways use taxonomic information to provide new insights into nutrient flow		**Very good**
Goal 7 Conceptual frameworks to infer ecosystem scale processes from microscale measurements	**Goal 9** Demonstrate importance of placing microbial interactions and nutrient flow in an evolutionary framework		**Good**
Goal 8 Rates of processes can be determined from molecular measurements	Goal 6 Routine use of proxies to attain comprehensive view of multiple pathways in ocean processes		Discontinued

Note: Goal statements have been shortened, please refer to full text in Table 4, Appendix E
Source: Compiled by Science-Metrix using the MMI expert panel report

Laboratory and field experiments aimed at goals 1 and 4 have led to deeper understanding of the microbial impact on nutrient flow and ecosystems, and opened the field for future work and new questions. MMI-funded researchers made excellent progress in developing single-cell methodologies. For example, new strategies in single-cell sorting were developed that rely on organism morphology, on chemical fingerprint, or on tagged proteins. These sorting advancements, along with other single-cell methods, led to the cultivation and sequencing of numerous un-cultured and under-sampled microbial groups (e.g., single-cell eukaryotes, archaea, bacteria). Several examples of newly developed single-cell methods that have led to better visualization and understanding of *in situ* microbial transformations and interactions were also noted by the panel. The detection, characterization of nutrients (e.g., dissolved organic matter), and lateral resolution (e.g., at the micron level) for visualizing substrate uptake and transfer has greatly improved.[70] Regarding goal 2, the panel deemed it an "ambitious project" typifying "high risk/high reward." To date, very promising progress has been made for diatoms, a choanoflagellate, two ciliates, and the protalveolate *Perkinsus*.[71]

Goal 10 was rated by the panel as "very good-to-excellent." Building on key innovations from Phase I (e.g., protein and lipid profiling, tackling specific organic–inorganic complexes and processes), Phase II grantees could link high-resolution organic and inorganic matter profiling with gene expression studies, and/or with visual identification of the key agents involved, to enable new findings. MMI PIs were "more integrative and innovative than the field at large" because they connected microbiological analyses with high-resolution organic matter composition studies, which were not integrated before. The panel stated that further progress could be made by experimenting with complex enrichments and mesocosms, and by studying the microbial metabolome and which chemical signals are available for intra- and interspecies or even inter-domain communication.[72]

Goals 3 and 5 both received a panel rating of "very good." For goal 3 this rating is mainly based on the capacity of the program to tackle a massive challenge: effectively modeling the immense complexity of marine microorganisms at varying scales in the ocean. As stated by the panel, "The individual projects have largely made significant progress, but the major challenge of nesting the many scales and variables of interest means that the goal is both attainable and unattainable."[73] Part of the challenge is that achievement of this goal as stated "will require massive investment and perhaps multiple generations. However, the goal of moving the needle on computational models on this topic has been possible."[74] For goal 5, MMI investigators discovered the activities of taxonomically and functionally different organisms by looking at single cells, a micron-scale ecosystem, and coastal ecosystems. MMI researchers confirmed the need for new tools because using bulk geochemical measurements in natural systems did not provide the precision necessary to assign function to individuals. The development of new, and optimization of existing, micro-analytical methods led to ground-breaking research tracing carbon and nitrogen across different trophic levels. However, the panel said that "linking taxonomically identifiable and functionally relevant units to rates of transformation and fluxes still remains elusive."[75]

Finally, a rating of "good" was given to goals 7 and 9. The panel said that while some projects under goal 7 demonstrated components of a conceptual framework as targeted, overall they lacked a more direct or explicit articulation of the framework as stated for this goal. The panel also noted that "the synthesis activities encouraged in the final stages of Phase II funding would be a timely and strategic means for shaping this framework."[76] Regarding goal 9, the panel said "few MMI investigations have specifically provided evolutionary perspective, although nearly all have the capacity to illuminate the evolutionary basis of marine microbial ecology." The panel went on to highlight a few specific projects that could be pushed to build an evolutionary perspective.[77]

The Marine Microbiology Initiative's role in the emergence of marine microbial ecology

Having examined individual TPOs, another way to look at achievement of the overall 2019 goal is to look at MMI's contribution to the evolution of the field toward an eco-systemic approach to the study of marine microorganisms. Since MMI began, the field has evolved considerably. In the words of the panel, "a new and vibrant field of marine microbial ecology has emerged, providing unprecedented opportunities to understand how microorganisms interact with cycles of carbon, nitrogen, and other elements in the oceans."[78] Bibliometric analysis further illustrated this evolution, showing publications focusing on microbe–microbe interactions and their influence on the flow of nutrients. Specifically, an analysis of trends in the number of marine microbiology papers published on the topic of microbe–

microbe interactions clearly showed that a shift toward a greater emphasis on microbe–microbe interactions occurred between Phase I and Phase II, in line with MMI's 2019 goal. According to MMI staff, this change might have been induced as early as 2012, not because of MMI Phase II papers, but rather because of a transition in the type of research performed by MMI grantees near the end of Phase I. This change prompted MMI to think about microbe–microbe interactions as a new focus area.[79]

Analysis also showed that MMI made a significant contribution to growth at the US and world levels in this research area. When excluding MMI-supported work from the analysis of microbe–microbe publications, growth was smaller at both levels. MMI generated slightly more than three times as much growth as expected at the US level given its share of US output in this topic. At world level, it generated slightly more than twice as much growth as expected. Similar findings held true for the study of nutrient flow, although smaller changes were observed.[80]

In addition to expanding the field, MMI-supported research on microbe–microbe interactions and nutrient flow was also the most impactful compared to that of other funders. Impact scores for the Moore Foundation and for MMI Phases I and II (combined and separately) were the highest in both topics across nearly all bibliometric indicators; when not in first place, they still scored close to the highest-ranked funder.[81]

Establishing a new paradigm

Regarding the overarching 2019 goal, the evaluation found that MMI is on the way toward establishing a new paradigm by uncovering the underlying principles that govern microbial interactions and nutrient flow. The evidence presented above on TPO level of achievement, as well as on how MMI has helped expand the field, already supports this finding. The expert panel also rated progress toward the overall goal as "excellent" based on the "range of exemplary studies advancing the toolbox to link organisms and matter transformations."[82] Further evidence comes from the 2015 internal strategic review, where two MMI examples of new principles that sit at the interface of nutrient flow and microbial interactions are given.

1) Virus infection in a certain phytoplankton group leads to greater shell calcification, resulting in increased carbon export to the deep sea, which directly links an interaction to a critical biogeochemical process that controls how much carbon dioxide microbes draw from the atmosphere into the ocean. This finding is important for understanding greenhouse gas dynamics.

2) Another new conceptual understanding is about what controls the growth of phytoplankton populations. An MMI-supported team made a strong case that the growth of photosynthesizing microbes and the consequent flow of carbon in the sea can be controlled not only by predation and nutrient limitation, but also by unique chemical communications signals that influence microbial behavior. This concept represents a profound new principle for the field.[83]

Finding #8: MMI's diverse grant-making approaches embraced collaboration and multidisciplinarity, combined with a commitment to high-risk and long-term research. These approaches have generated innovative knowledge frameworks, knowledge production and the sharing of methods, data sets and technologies. This has contributed to new knowledge being taken up by the MMI community and the utilization of new technologies, techniques, tools, methods and computational models.

While EQ6 (achievement of outcomes) does not explicitly mention the MMI theory of change (see Appendix D), it is appropriate to gauge achievements against the logic model (Figure 8) to validate the theory. Briefly, the MMI logic model proposes that MMI inputs and activities (e.g., program design, strategies and grant-making approaches) along with the MMI approach to research management (discussed in detail under Finding #11 below) should lead to certain outputs (such as knowledge advancements), and then to outcomes that mirror the TPOs (e.g., knowledge uptake, testing and use of new methods, tools and techniques, and eventually demonstrating new scientific principles). Some key examples are presented here to demonstrate that this chain of logic generally occurred as hypothesized.

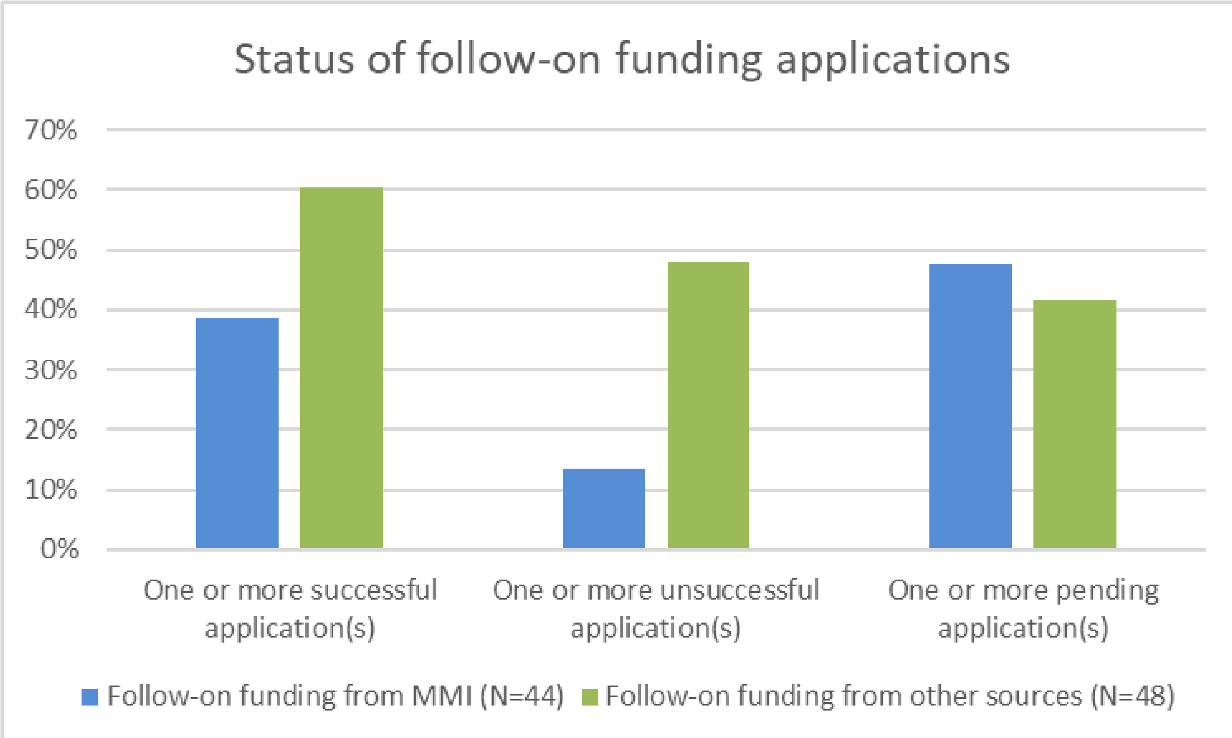
- From the bibliometric perspective, the collection of MMI-supported work boasts a top ranking for scientific excellence and global citation impact. MMI-supported papers were also frequently found in the most highly cited journals. The high scientific excellence scores for MMI grantees indicate that the initiative funded highly influential researchers. In other words, this shows that MMI inputs and activities as listed in the logic model were successful in targeting the intended group of people. Further, the high scores suggest that MMI has succeeded in supporting high-impact research that is widely taken up by the marine microbiology community.[84] The targeted outputs (innovative methods, data and knowledge) were produced and shared, leading to the outcome of knowledge uptake (citations) by the marine microbiology community.
- As an example of the logic model outcome "new methods, tools, techniques and data sets developed and used," one of the most frequently referenced achievements in the interview data was the development of an instrument using high-throughput techniques to measure the presence of specific nutrients in single-cell organisms. This instrument (known as CLIO) enabled discovery of multiple biomarkers that signal the presence or absence of specific compounds and nutrients based on the underlying biochemistry. The potential of this achievement is far-reaching in terms of understanding how microbial communities adapt to changes in their aquatic environments and mapping this on a global scale.[85]
- Regarding the outcome "new computational models developed and used," a frequently cited community resource tool was the Microbial Eukaryote Transcriptome Sequencing Project (MMETSP), an online database of gene expression patterns of individual eukaryote species that researchers could download in whole or in part and use as a custom database (see also Figure 1 above). (While MMETSP was strategically envisioned during Phase I, it occurred during the timing of Phase II). Also of note is the work of one MMI researcher who was involved in two MMI community resource projects, iMicrobe and VERVE Net, that were subsequently leveraged to obtain funding from other sources (including the NSF) to make many community data sets accessible through one cyber infrastructure.[86]
- In terms of the outcome "exemplary lab studies that provide insights and demonstrate new principles," MMI experimental lab research found that in terms of isotope signatures, dinoflagellates resembled other taxa of marine algae, suggesting the presence of a governing enzyme other than Rubisco or other biophysical/biochemical processes at work. This finding could significantly change current thinking about aquatic photosynthesis and carbon cycle models. A second example reflects an improved understanding and characterization of microbial interaction along a trophic continuum, specifically mixotrophy. The research appears to support

the notion of a continuum of pure plant-like to pure animal-like organisms in the ocean, contrary to the prevailing plant–animal dichotomy on land and in the sea.[87]

Finding #9: Numerous grantees who had received follow-on funding to their MMI-funded research from government agencies attested to the quality and the relevance of the MMI-supported research.

To conclude the discussion on this evaluation question (EQ6 – achievement of outcomes), note that the logic model also proposes a 2015–2019 outcome that researchers are recognized and receive follow-on funding for their MMI-supported work (Figure 8, Appendix D). This was indeed found to be the case. An analysis of available grantee narrative reports shows that grantees of 37 (out of 45) grants reported having applied for follow-on funding. The organizations to which grantees in this sample submitted the highest number of applications for additional funding were the NSF, the Simons Foundation and NASA.[88] The interview data are also replete with examples of principal investigators securing follow-on funding from other sources in combination with, or subsequent to, completing their MMI research. Those funded under the investigator award were particularly appreciative that it provides them with sufficient flexibility to undertake a number of related research projects simultaneously and to leverage those with promising preliminary data to obtain additional funding for the researchers involved and the lab in general.[89] Finally, most survey respondents (78%; n=92) said they applied for additional funding from multiple sources to continue the work of their MMI-funded project.[90] The status of those applications is presented in Figure 6.

Figure 6 Survey question: Please specify the status of application(s) for follow-on funding from MMI/from other sources



Note: MMI program staff note that the survey took place during an active MMI request for proposals, which likely influenced the number of pending applications to MMI.

Source: Compiled by Science-Metrix using MMI e-survey data[91]

4.2 EQ7 To what extent can results thus far be reasonably attributed to the MMI interventions (strategies, approaches, grants, workshops, and other program efforts)?

Finding #10: The outcomes achieved can be strongly attributed to MMI funding. However, external factors such as public and private infrastructure and funding, the caliber of grantees and their professional networks, and the decreasing cost of genome sequencing have also positively influenced overall achievement.

As seen in the previous sections, there are many qualitative examples indicating that MMI's intervention in the field of marine microbiology has generated the expected outcomes. From the interview data, all interviewees said that MMI awards were at the heart of their research interests and, for about half, have shaped their research portfolios.[92] This is a weighty statement coming from principal investigators who manage large, multi-staff laboratory operations supported by many funding sources with highly complementary projects. As summed up by the expert panel, "One undeniably unique contribution MMI has made in the field of Marine Microbiology is the investment in the development of tools, techniques, and computational resources that will increase the accessibility of systems limited by technology and open research in those areas."[93] There is also quantitative evidence attributing results to MMI funding. A longitudinal bibliometric analysis examined grantees before and after they received MMI support and found the following:

- Very high scientific impact scores for grantees before MMI support, indicating that grants targeted outstanding researchers from the outset.
- MMI grantees (Phase I and II) experienced a large increase in their average of relative impact factors during the period of MMI support, suggesting that MMI contributed to increasing the visibility and quality of their publications.
- All MMI grantees increased the proportion of their total scientific production on microbe–microbe interactions under MMI support. The increases observed among MMI grantees were not matched by similar increases in the US or among the top producing researchers worldwide in marine microbiology over the same period. This suggests that MMI successfully supported the shift toward research on microbe–microbe interactions, in line with its 2019 goal. Findings for nutrient flow are similar (although the gap between the gain of MMI grantees relative to the control group is smaller).

Nonetheless, external influences were also an integral part of outcome achievement (and were hypothesized in the logic model). For example, government and private funding for research infrastructure and training plays a critical role, including "NIH- and NSF-supported databases, government-installed data transmission lines and a fleet of research vessels supported by NSF and the National Oceanic and Atmospheric Administration."[94] Other complementary resources include the Simons Foundation time-series site (previously directly supported by NSF) and the Schmidt Ocean Institute research vessel (refer to Finding #3 on complementarity for more detail). Internal interviewees also noted that since MMI Phase I and over Phase II, gene sequencing has become cheaper. This reduced the cost of conducting research and made new areas of research more accessible.[95] Finally, for most of the principal investigators, certain *a priori* factors such as past research experience, large professional networks and collaborations established over a long career also positively influenced outcome achievement.[96]

Finding #11: The MMI research management approach—that is, flexibility, support for convenings, willingness to engage long-term and high-risk commitments—greatly contributed to knowledge exchange and collaborations among MMI researchers and thus indirectly contributed to outcome achievement.

Several aspects of the research management approach (called "research process characteristics" in the logic model (Figure 8, Appendix D)) have already been discussed in this report. For example, it was shown that the Moore Foundation's approach to research management involves long-term commitments (especially in the MMI investigator awards and multidisciplinary team grants, see Finding #4), is risk-tolerant (Finding #6), and promotes interdisciplinarity/the use of multiple techniques (Finding #5). Below, examples illustrate that the remaining research process characteristics in the logic model—namely, fostering interactions, flexibility and MMI staff support—indirectly contributed to outcome achievement.

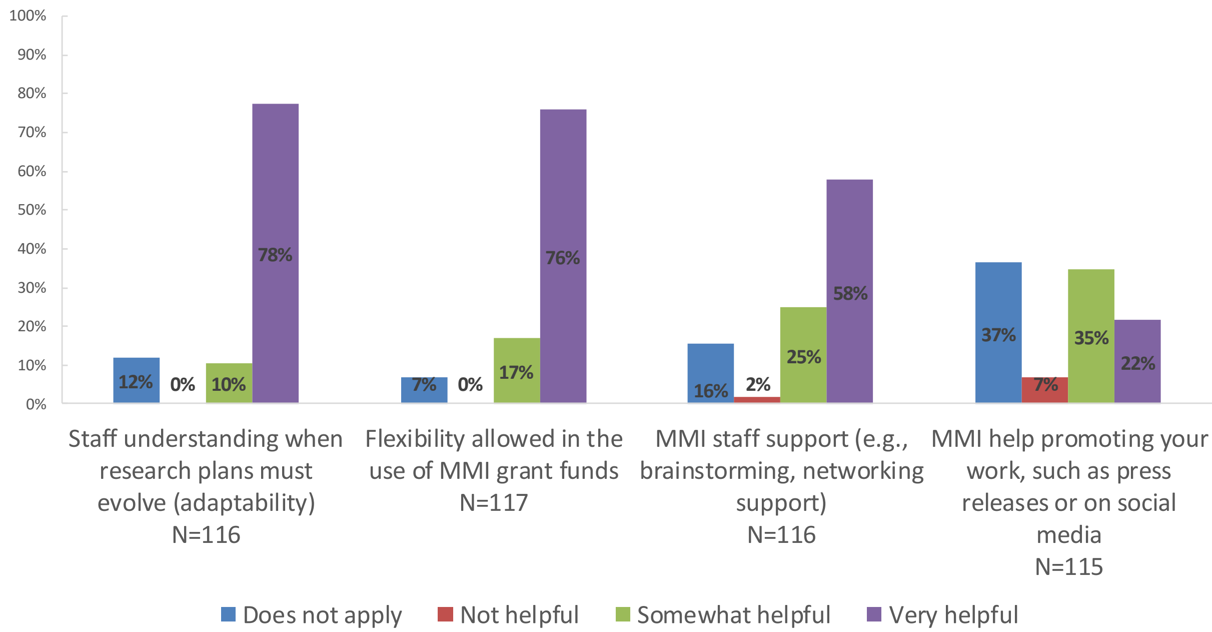
Fostering interactions: Multiple documents (e.g., two Phase II grants for convening activities, MMI funding allocated to lectures, training sessions and more than 60 conferences, post-workshop satisfaction surveys)[97] show that MMI continuously organized or funded meetings, events and other knowledge-exchange activities. These aimed to foster dialogue and inspire new ideas among the marine microbiology community. Two examples of convenings discussed in the grantee interviews were the annual MMI investigator award meetings and bimonthly virtual conferences held for the EMS grantees. The indirect benefits cited for the investigator meetings included staying informed on the latest developments in MMI-supported research, the sharing of information through networking, and establishing collaborations based on common interests. The main benefit identified for the EMS conferences was the sharing of methods, techniques and progress on the achievement of outputs related to the MMI-funded research. Networking, establishing collaborations and knowledge sharing were also listed as the primary benefits of attending other general convenings, such as workshops and symposia held in conjunction with MMI conferences. About half of the principal investigators also noted the importance of these types of activities to expose their lab staff, including students and technicians, to new ideas and opportunities to present work.[98]

These sentiments were generally shared by the broader survey population. On average, survey respondents participated in 2.9 MMI meetings/workshops, 2.7 webinars and 8 conferences, symposia and town halls hosted or run by MMI, and 1.7 joint meetings with other research organizations. Survey respondents who participated in these MMI convening activities (81% n=82) were asked to specify the impact. These activities were said to be most useful for

- staying informed on latest developments in marine microbiology (87%; n=85),
- social networking (81%; n=79),
- increased collaborations (66%; n=65),
- project cross-fertilization (64%; n=63), and
- identification of pressing questions and technological needs (62%; n=61).[99]

Flexibility in funding/approach: Survey data also pointed out the importance of a flexible, adaptable approach to research, which the majority of survey respondents (78%) found very helpful (Figure 7).

Figure 7 Survey question: How helpful have you found each of the following in implementing your research?



Source: Compiled by Science-Metrix using MMI e-survey data[100]

This flexibility was demonstrated in two ways. First, flexibility was allowed in the allocation of resources to MMI projects; up to 20% of the total budget could be reallocated without MMI permission. Researchers could "allocate the annual funds based on needs."[101] In other words, they could move funds from one budget item to another, depending on the project needs for a given year; for example, they could allocate more funding to equipment purchases the first year and to salary costs the subsequent years, once team members had been recruited. Second, MMI also allowed for research goals and deliverables to adapt as the research evolved. Grant development instructions for funding applicants specify that—for the investigator award grants—the researchers "do not need to feel constrained by the details of (their) application if (their) ideas have evolved since then."[102] The instructions stipulate specifically that the investigator awards do not have "outputs," or "concrete deliverables,"[103] indicating an understanding that some research objectives or milestones might change along the way and that this would not affect funding.[104] The flexibility to adjust budget and to undertake simultaneous projects and leverage only those with promising preliminary data was greatly appreciated by the interviewed principal investigators.[105]

MMI staff fill gaps, find synergies: MMI staff are embedded professionals with PhDs in ocean science and existing networks of professional relationships. Staff strategically attend conferences in both the field and other areas of possible MMI interest. When they engage with the community, staff members know enough about the science to be able to determine the promise of ideas proposed. Staff members also reported that they search for and initiate ideas for research projects. Staff familiarity with the status of current and completed grants and the MMI time-phased outcomes means they can identify gaps and ideas for new research. Staff members then target their attendance at meetings and pertinent talks according to identified priority areas.[106] From the interview data, almost all grantees were very appreciative of the relevant academic training of MMI staff, their dedication to the field, awareness of research trends, broad network of contacts and familiarity with research funding barriers. Staff were perceived by interviewees as nimble in addressing identified gaps and opportunities, and supportive of synergies across the grant-making approaches through the creative use of funds to support the development of scientific instruments and the purchase of equipment to advance a given research agenda. Interviewees said that MMI staff actively proposed interdisciplinary collaborations at the proposal review stage and in discussions about future research projects.[107] Finally, the ability of the staff to seek out opportunities was also highlighted by the expert panel, who said, "the MMI program officers adaptively manage their portfolio to create synergies between projects and enhance interdisciplinary research that has increased the impact and created synergies where the wholes exceed the sums of their parts."[108]

4.3 EQ8 What unintended consequences (positive and negative) have resulted from MMI's interventions?

Finding #12: MMI-developed techniques, tools and methods were used beyond the marine microbiology community, contributing to human, terrestrial and plant microbiome fields. Also noteworthy was the career development of a next generation of highly qualified professionals.

One intended outcome of MMI was that new knowledge created under the initiative would be taken up by the marine microbiology community. Unexpectedly, there are several instances where MMI knowledge reached a wider audience. For example, nearly 80% of papers referencing MMI community resource outputs fall in the periphery of marine microbiology, indicating that these resources are reaching out broadly to researchers who are not at the core of the marine microbiology field.[109] These periphery fields included evolutionary biology, microbiology and general science & technology.[110]

The expert panel also said that "marine microbiology, led by MMI investigators, has pioneered single-cell quantitative approaches (e.g., nanoSIMS), metagenomic, and microbiome sciences, providing methods and guiding concepts to the human, terrestrial, and plant microbiome fields."[111] For example, the 2015 internal strategic review—which was informed by experts in the field—indicated that MMI-initiated discoveries and approaches paved the way for study of human microbial ecosystems through NIH's Human Microbiome Project.[112] Internal interviewees reported that MMI-developed bioinformatics approaches were taken up by the human microbiome community, as well as concepts such as considering a full microbial community to understand energy transfer (as opposed to examining individual species of microbes).[113] Furthermore, MMI funding was mentioned when the White House announced its National Microbiome Initiative[114] in May 2016 to foster the integrated study of microbiomes across different ecosystems.

Another noteworthy outcome, not originally included in the MMI theory of change, is the fact that a new generation of highly qualified professionals has been supported through MMI's investment. Training of these professionals occurs via early career focused events, exposure to conferences and collaborations. For example, MMI Phase II supported two summits for early career researchers to share unpublished work and methods, network and explore ways to collaborate across disciplines, discuss interdisciplinary science through the lenses of maximizing scientific impact and leadership, and foster participation in the open science movement.[115] About half of the grantees interviewed said that they send their postdoctoral and doctoral students not only to MMI events but also to other funders' conferences to disseminate their MMI research findings and to help develop students' careers.[116] In this way, MMI training can also enable subsequent promotions such as faculty career paths.[117]

4.4 EQ9 What challenges has MMI encountered, and what adaptations have been made as a result of these challenges? What are the most significant lessons learned?

Finding #13: The MMI Phase II portfolio evolved as the science and technology evolved (e.g., reframe allocation, adjusting TPOs), demonstrating adaptation. MMI also adapted to the Phase I assessment of the grantee selection process by reaching out to the broader community to gather research ideas and implementing competitive selection processes. However, there remains a well-founded perception of exclusivity in the allocation of grants within the marine microbiology community.

The evaluation found that since MMI Phase II began, its design, strategies, approaches and expected outcomes were reviewed, modified and/or adjusted if necessary to overcome obstacles or to meet the evolving needs of the marine microbiology field. Several key examples demonstrate a challenge faced and a subsequent adaptation.

- In 2014, following the launch of the investigator awards and multidisciplinary team grants, "MMI reviewed its strategies and implementation approaches"[118] and identified gaps in the execution of Strategies II and III. This motivated a request for an additional $30 million allocation to fill the gaps, aiming to

  > 1) accelerate the rate of development and widespread adoption of new marine sensors and instrumentation; 2) develop new tools and enrich the ecosystem of bioinformatics cyberinfrastructures; and 3) amplify the new techniques and methods currently under development through the Investigator and Multidisciplinary project portfolios.[119]

- In 2015, internal review of achievement against the 2015 goals precipitated an adjustment of the time-phased outcomes. Some were modified for 2019 and two TPOs were discontinued (see Appendix E).[120] Specifically, according to internal interviewees, TPO 6 was discontinued because it had become less important, and TPO 8 was discontinued because it was determined to be too difficult.[121]
- A 2012 evaluation noted that under Phase I, MMI was criticized for not reaching out to the broader marine microbiology community in the selection of awardees.[122] MMI learned from this experience and used open calls in Phase II to widen its pool of ideas and grantees. Interview data from both internal MMI staff and from grantees confirmed that the Phase II project selection process shifted considerably from past practice, now actively engaging members of the community through these open calls, to address research funding gaps and/or novel research ideas.[123,124]

Regarding this last point, the 2012 evaluation's survey of MMI grantees found "44% [of grantees] stated that the Phase II [selection] process was not transparent, indicating that the current methods for communicating to the community are not optimal."[125] It should be noted that this response refers only to the Phase II Request for Ideas grants, as the investigator awards competition was not announced until the end of 2012. The 2012 evaluation cautioned that "if the selection process is perceived to be uninformed by broad expertise in the field of marine microbiology, the perception problems will be exacerbated."[126] It is also possible that this perception is due to the number of grantees who have received multiple MMI awards over the whole period of Phase I and II. A majority of Phase II investigator award grantees (64.7%) received Phase I support, and this also accounted for the majority (62.1%) of Phase II funds allocated in total to investigator awards. Also, 82.4% of Phase II investigator award grantees received multiple grants over the whole Phase I and Phase II period. Overall (across all grant types), 20% of Phase II grantees received multiple grants over the course of Phase I and II combined accounting for 58.9% of Phase II funding. A majority of Phase II investigator award grantees (64.7%) had received multiple Phase II grants, while 14.1% of Phase II grantees overall received multiple Phase II grants accounting for 47.9% of the funding. Details of the analysis can be found in Table 7, Appendix F, with the above noted percentages highlighted in yellow. The continuity of funding across the two phases, the relatively large dollar value of investigator awards and the incidence of multiple awards to some individuals were mentioned by a few interviewees who were concerned that this MMI grant distribution split the community into the funded "haves" and the unfunded "have-nots."[127]

Another possible reason for the perception of exclusivity in the allocation of grants is that international partnerships were not central to MMI's design within the time frame of this evaluation. Grantees did not increase their international co-publications any more than comparable groups while receiving MMI support. Granted, in a country as large as the US, there are numerous opportunities for beneficial collaboration, reducing the need for US researchers to target international partnerships.[128] Nevertheless, the expert panel noted that MMI has "potentially underutilized their flexibility in taking advantage of international collaboration opportunities and in the delivery of integrated products that communicate the vision and exceed the sum of the parts (i.e., synthesis)."[129]

Finding #14: There is an opportunity to develop a more explicit theory of change, which would allow for the systematic collection of performance data to measure outcome achievement on an ongoing basis. Although the articulation of time-phased performance outcomes was helpful, they were not sufficiently operationalized.

With an eye toward the future, the evaluation found that opportunity exists to better measure outcome achievement and MMI impact. In the 2012 evaluation, a recommendation on maximizing MMI impact stated that consideration be given to determining "which metrics can be monitored to assess impacts and success."[130] In this regard, a performance measurement strategy for MMI Phase II was not operationalized beyond the articulation of TPOs, and limited performance data were collected, analyzed and documented for ongoing performance management and decision-making or to be shared with the evaluation. The information that was available on achievement stemmed from the 2015 internal strategic review and final grantee narrative reports. The strategic review did not specify the sources, methodology or performance indicators used to assess the 2015 outcomes. Additionally, this review mainly represented the MMI internal perspective.[131]

The review of the MMI Phase II grants database provided information on the extent to which Phase II grants *were expected* to achieve the strategies and logic model outcomes, rather than information on *actual* outcome achievement, except for final reports. In the absence of standardized performance measurement data, the evaluation reviewed grantee narrative reports, grant close reports and other summary documents, but it was not possible to perform a systematic assessment of MMI's achievement of actual outcomes to date due to inconsistencies in reporting of project achievement against time-phased outcomes. While grantee narrative reports generally included a detailed summary of the progress made against project-specific outputs and outcomes, grantees did not systematically report on the progress made against time-phased outcomes (although closing reports do so),[132] making it impossible to aggregate the grant-specific outcome data. The absence of an overall MMI progress summary (annual or otherwise) and performance data linked to an explicit theory of change was indicative of an undeveloped performance measurement system, which also hindered the ability of the evaluators to assess MMI impact.

5 Findings – Issue 3: Potential path forward

This section of the report examines future opportunities for MMI (Section 5.1), including ways to build on previous MMI work (Section 5.2).

5.1 EQ10 Are there future opportunities in the realm of marine microbial ecology that may be worth pursuing by MMI? What are the relative strategic and scientific risks and potential gains of those opportunities?

Finding #15: MMI has an opportunity to build on its success in marine microbial ecology, aiming to understand and predict the cascading impact of microbial variability on marine ecosystems in space and time—past, present and future—in order to understand ocean change. To pursue this opportunity, a number of impeding factors must be addressed through a systematic sampling of diverse habitats, improved instrumentation and access to data platforms, and building predictive marine ecosystem models that integrate organisms, consortia and the ocean environment.

The evaluation gathered many ideas on future opportunities in the realm of marine microbial ecology. Because these were so varied and no single unifying theme emerged, the opinion of the expert panel is presented here in the body of the report. An overview of the other suggestions that emerged by line of evidence is presented in Table 8, Appendix F.

The expert panel recommends MMI build on its advances to "understand and predict the cascading impact of microbial variability on marine ecosystems in space and time – past, present, and future – in order to understand ocean change."[133] According to the panel, the benefit of linking microbial ecology to present and future ocean states lies in dramatically improving human interaction with, and benefit from, ocean biota. Because a full conceptual framework to infer ecosystem scale processes from the microscale is still lacking (i.e., TPO 7), the panel recognized that more integration is needed from "genes to cells to communities to ecosystems, each with its own sets of tools, experts, and biases." This will also demand "novel expertise on effective integration of those resources and opportunities across time and space, and require that the [Moore Foundation] continue to search out the talent to fill these gaps."[134]

The panel was also asked to comment on the theme of symbiosis, which the Moore Foundation is considering as a topic of future interest. While recognizing the considerable potential of this topic, the panel cautions that

> it requires focus, since "Symbiosis" covers a remarkably broad set of biological relationships. Some of the projects within and discoveries from the MMI are already very relevant advancements to the field of symbiosis research, and [the panel] encourages development of a unifying theme focusing on partnerships between single-cell eukaryotes and bacteria or archaea. This would require development of, for example, new model systems for studying microbial cell-to-cell interactions, and could include consideration of other relevant topics: organelle evolution, gene exchange and gene streamlining across partners.[135]

One potential focus area within symbiosis would be the concept of microbial consortia, an assemblage of microorganisms where the association of the different organisms is of benefit to all. As these consortia play a major role in the carbon cycle, their study would enable a better understanding of the microbiology of the poorly studied deep sea. According to the panel, focusing on both marine and freshwater consortia could "develop new concepts of functional symbiosis that would include the full range of interactions, from dynamic microbial associations to persistent endosymbiosis."[136]

In any case, the way forward is studded with impeding factors (listed below) that can be addressed as MMI work continues.[137,138,139]

- A focus on different habitats has led to a partial fragmentation in the field (e.g., deep sea, blue water, coastal). A more balanced sampling of different zones would contribute to a better understanding of biological diversity and symbiotic interactions in large-scale ocean processes.
- Data accessibility in general remains an issue, and improved data sampling and coverage was cited as an ongoing need by researchers.
- Bioinformatic analytical tools and pipelines may not be sufficiently user-friendly and standardized to ensure uptake by the wider community. Training on the proper use of bioinformatics tools could avoid making incorrect inferences about microbial activity.
- There is a need for more long-term time series of sequence data, to enable robust predictions of the dynamics of microbial life in the future ocean.
- Few laboratory model systems exist to study the response behavior of marine microbes; meanwhile ecosystem models generally make little use of the vast knowledge that now exists on marine microbes and their interactions.
- Continued work depends on access to expensive research ships, and/or instrumentation, some with long lead times and planning cycles that are not compatible with rapidly developing science. Access to instrumentation particularly remains a barrier for *in situ* analysis.

5.2 EQ11 How would MMI's work to date inform and shape these potential future opportunities?

Finding #16: MMI can continue to be a leader in the accelerating marine microbial ecology field, drawing on its risk-tolerant, flexible management approach, as well as building on its past scientific and technological breakthroughs. The expert panel suggested three levels of research that would build on previous MMI work: gene, community and ecosystem levels.

MMI's work to date has already helped shape the emergence of several research topics including:

- novel applications of next-generation sequencing methods;
- the use of functional gene abundance in studying the flow of nutrients (in particular de-nitrification) and primary productivity; and
- the study of microbe–microbe interactions (in particular virus–bacteria interactions).[140]

With respect to symbiosis (as discussed in the previous finding), the bibliometric analysis found that while publication output in this topic increased overall (2004–2015), it did so at a slower pace than the increase in overall research output in marine microbiology. This suggests that the relative emphasis placed on symbiosis diminished slightly over time relative to other topics. If large governmental funders are disinvesting from research on symbiosis, investigators who are active in this topic may indeed need support from alternative sources.[141] To this end, MMI is currently the only sizeable source of private funding in this area and ranks highest in terms of scientific impact on nearly all impact metrics (recall Table 1, Finding #3).

Considering the future opportunity as proposed by the expert panel—to explore the cascading impact of microbial variability on marine ecosystems in space and time—MMI could build on three distinct levels of previous MMI work.

1. Gene level: Single-cell methods/tools/approaches as developed by MMI researchers can be expanded to gain a mechanistic understanding of microbial communication. These efforts could consider symbioses between single-cell eukaryotes and single-cell prokaryotes (bacteria, archaea), interactions that hold promise for studying organelle evolution and synthetic biology. Gene-level study could also consider viruses as evolutionary drivers, shaping communities through natural selection on genomes.[142]
2. Community level: Here, MMI-supported tools could be applied to examine interactions between microbes and macrobes. "Tools developed by MMI can facilitate the use of and infuse new techniques into longer time series observations and investigations."[143] For example, researchers could use environmental DNA or archived samples to study the composition of communities, to explore species co-occurrence and environmental function, and to "discern persistent versus transient associations (e.g., microbial and consortia, symbiosis) in time and space."[144]
3. Ecosystem level: MMI offers opportunities to incorporate theoretical ecology and evolution into microbial ecology, adding increased rigor and scaling expertise to existing approaches.[145]

Finally, other general areas where MMI was well positioned to build on its previous work included scientific instrument development and continued efforts to stimulate careers of promising young investigators.[146] Overall, building on its risk-tolerant, flexible management approach (Findings #6, 11) and considering the progress that has already been made toward the TPOs (Figure 5), MMI can endure as a leader in the accelerating marine microbial ecology field.

6 Conclusions and recommendations

The conclusions presented here are grounded in the findings on initiative design and implementation, outcome achievement and the potential path forward for MMI.

Initiative Design and Implementation

> **Conclusion #1: MMI reframed its research focus and goals for Phase II with broad participation from the marine microbiology community. MMI has since adapted its strategies, grant-making approaches and implementation processes in an ongoing and continuous manner. No discernible differences were identified in the relative effectiveness of the strategies, while the multidisciplinary team and investigator award grant-making approaches were determined to be the most effective in achieving expected outcomes.**

The MMI Phase II design and subsequent adjustments were undertaken in close consultation with the marine microbiology community. This resulted in an increased research focus on microbial interactions and nutrient flow, which was well aligned with the 2019 overall goal for the initiative. MMI assumed a leadership role in support of high-risk/high-reward research, such as EMS, with substantial long-term funding to explore emerging research areas and undertake challenges not accessible to most public and private funding organizations. Synergy, interdisciplinarity, and new technologies, techniques, tools and methods were visible across all grant-making approaches and contributed to the overall effectiveness of the portfolio. Multidisciplinary team grants and investigator awards have been the most effective in achieving expected outcomes, while the community resources and other tools have been taken up by the marine microbiology community and beyond. [Supported by findings #1–6]

Recommendation #1: That MMI continue the many aspects of its research management approach that have resulted in the outstanding scientific and technical achievements documented in this evaluation study, while elaborating more explicitly how each strategy is expected to contribute to the achievement of outcomes.

> **Conclusion #2: Two areas were identified with regard to implementation processes that could be improved to address the concerns of the marine microbiology community and to support management decision-making. One is how the relatively small number of MMI grantees is perceived by the marine microbiology community; the other relates to the challenge of establishing a system to assess the performance of basic research.**

MMI management encountered some challenges and made the necessary adjustments in response to technological changes and scientific advancements. Further management attention is still needed to (1) address the perception within the marine microbiology community of exclusivity in the allocation of grants, and (2) develop a more explicit theory of change and standardized performance measurement system. [Supported by findings #13–14]

Recommendation #2: That MMI develop a more explicit theory of change for its management approach and funded research, including a sequence of expected outcomes, and a standardized performance data collection and analysis system that will allow for the continuous monitoring and periodic in-depth assessment and reporting on expected outcomes.

Outcome Achievement

> **Conclusion #3: Very good to excellent progress has been made toward the achievement of most 2015 and 2019 time-phased outcomes, which portends well for the achievement of the 2019 goal. MMI-funded research has developed new knowledge that has been highly cited, new instruments, tools and data sets have been taken up by the marine microbiology community and promising steps have been taken to develop genetic systems in some single-celled marine organisms. The evaluation has determined that the excellent achievements can be attributed to MMI grant funding, although there were some positive external influences and research management approaches that contributed to the observed outcomes.**

Excellent progress has been made toward the achievement of the 2019 goal to establish a new paradigm by uncovering novel principles about microbial interactions and the transformation of nutrients. There has been an improved understanding of microbial interactions at a single-cell level and organic matter composition and cycling, while progress continues in the areas of theory, synthesis and modeling of biological interactions. The development and utilization of new technologies, techniques, tools, methods and computational models by MMI researchers has been instrumental to these achievements. In addition, MMI has had an unexpected influence on microbial ecology in other environments (e.g., human, terrestrial, plant) and some other areas of biology and ecosystem science. While these outcomes can be strongly attributed to the grant funding itself, the MMI research management approach and external factors have also positively influenced overall outcome achievement. [Supported by findings #7–12]

Recommendation #3: That MMI continue to engage independent expert panels to assess outcome achievement and the path forward, based on their knowledge of the science and MMI data from monitoring and other independent evaluations.

Potential Path Forward

> **Conclusion #4: Marine microbial ecology has been an accelerating field, in part because of MMI's achievements, and MMI has the opportunity to build on its high tolerance for risk and its strengths in innovative tool and model development by pursuing a new five-year goal to further understanding of ecosystem and ocean processes.**

The Moore Foundation has an opportunity to build on MMI's successes in advancing the marine microbial ecology field to better understand and model ecosystem and ocean processes in space and time. The challenge will be to integrate new research knowledge developed at all scales of microbial functions from gene to cell level, at the community or consortia level, and at the ecosystem to global level. Much remains to be accomplished to bridge cellular-level data collection, systems biology, computational modeling and theory development. Biogeochemical ecosystem modeling at the microbial community or consortia level holds much promise. [Supported by findings #15–16]

Recommendation #4: That the Moore Foundation continue to support research in marine microbial ecology focused on understanding and modeling the ecosystem at the microbial community or consortia level as recommended by the expert panel.

Appendix A: Profile of the Marine Microbiology Initiative

Marine microbes include a wide range of microorganisms, such as microalgae, bacteria and archaea, protozoa, fungi and viruses. They play a critical role in the transformation of chemical elements, the creation and degradation of organic matter and the recycling of nutrients in the ocean: activities that are essential to all other forms of marine life. Despite their importance, little was known about these microorganisms in the early part of the new millennium. The Marine Microbiology Initiative was thus created in 2004 to boost research efforts aimed at addressing these basic yet fundamental issues for the field. Under Phase I, MMI was allocated $145 million over 10 years (2004–2013) to fund research projects and supporting activities through three grant-making approaches: investigator awards, multidisciplinary expansion awards and high impact research awards. During this first phase, MMI focused on the question of "Who's there?" To this end, substantial support was targeted toward genome and metagenome sequencing at the individual microbe and whole-community levels.[147] MMI funding was provided directly to emerging and established principal investigators (PIs) with a proven track record in the marine microbiology field, as well as multidisciplinary teams.[148]

As the original funding allocation was largely expended by 2010, the Gordon and Betty Moore Foundation (the Moore Foundation) Board of Trustees decided to renew MMI for a second phase spanning 2011 to 2019, with an initial $75 million budget.[149] The initiative's objectives and theory of change were modified considering progress made against initial outcomes. The application of genomics technologies had allowed for major advances in the identification and observation of microbes in their environment, and it was thus time for the field to "move beyond focusing on a subset of community members or doing broad diversity surveys, and move toward understanding how the species present together contribute to an ecosystem's functions."[150,151] This "reframe" process was informed by consultations with thought leaders and ideas submitted by the broader international marine microbiology research community through a Request for Ideas. Thereafter, MMI shifted focus toward gaining a better understanding of the dynamics of the marine microbiology community.

A new long-term goal was defined to reflect this change: *"A new paradigm will be established for uncovering the underlying principles that govern inter- and intra-domain microbial interactions and that influence the flow of nutrients in representative marine microbial ecosystems."*[152] MMI Phase II operates on the assumption that it is the joint study of microbial interactions and nutrient flow that will most likely lead to major transformations of the field. In other words, the focus of MMI is (1) microbial interactions; (2) microbially mediated nutrient flow; and (3) the intersection of microbial interactions and nutrient flow. The aspiration of MMI is also intended to ultimately address an urgent need to make significant advances in these areas to help better understand how the oceans' and Earth's functions served by marine microbial communities (i.e., role in food webs and biogeochemical processes) are affected by major stresses such as climate change.[153]

MMI also defined a set of 10 time-phased outcomes to be reached by 2015 and another 10 outcomes following from each of the 2015 outcomes to be reached by 2019 (Table 4).

Dating back to 2011, challenges were foreseen that could prevent MMI from achieving its time-phased and long-term outcomes, including the following:

> an inability to grow most microbes in culture; limited ability to observe the distribution of most microbes; challenges observing the small time and space scales relevant to microbes and scaling those up to ocean-level processes; few genetically tractable experimental model systems; and difficulties determining relationships between microbes and the complex organic matter they produce and consume.[154]

MMI identified the following three strategies to help mitigate these issues:[155]

Strategy I: Overcome interdisciplinary barriers that currently hinder scientists from identifying and quantifying nutrients in the ocean, and from understanding how microbes interact with one another and the consequences of those interactions.

Strategy II: Support development of key technologies, tools, methods, computational modeling techniques, and theory needed to advance understanding of microbial interactions and their mediation of biogeochemical cycles.

Strategy III: Increase community adoption of genetics by supporting research to develop experimental model systems, an under-developed, yet powerful way to investigate interactions between organisms and the role of microbes in biogeochemistry.

Strategies I and II were launched in 2011 with the identification of the recipients of multidisciplinary team grants and investigator awards (the latter through an open competition).[156] An internal strategic review of MMI conducted in 2013 revealed that (1) substantial grant investments had already been made toward Strategy I; (2) there were gaps and opportunities for further funding Strategy II; and (3) despite "high potential for transforming the field," Strategy III had not yet been launched.[157] Another allocation request was thus submitted to the Board in January 2014 for an additional $30 million to address the gaps and opportunities within Strategy II and to launch Strategy III.

Unlike Phase I, MMI Phase II largely began with grants sourced through two open calls for ideas and proposals. First, MMI staff used the Request for Ideas begun in 2010 as a source to identify multidisciplinary projects that met the newly designed initiative goals. Second, staff ran a competition for a new cohort of individual investigator awards. Overall during the first several years of Phase II, the MMI team issued these calls for ideas and proposals to the broader marine microbiology community as well as making individual outreach to prospective grantees to identify research projects that best fit with their outcomes and the following grant-making approaches: (1) individual investigators who are current and emerging leaders in the field; (2) multidisciplinary teams that are developing new instrumentation, tools and technology; (3) community resources for the creation and sharing of data and tools of broad use to the community; and (4) projects that develop tools, methods and technologies, including an emphasis on those that accelerate the adoption and development of genetic tools to enable development of experimental model systems in marine microbial ecology. MMI also convenes groups of scientists around topics of key importance and sponsors workshops to promote scientific exchange. The following is a brief description of MMI's four grant-making approaches.[158]

Investigator awards

The investigator awards portfolio builds from the concept that providing emerging and leading researchers with the resources and flexibility to follow their scientific instincts and conduct cuttingedge, often risky research leads to innovative, high-impact science. MMI investigators are expected to use a diversity of complementary scientific perspectives and tools (such as molecular ecology, evolutionary theory, geochemical analyses and computational modeling) to shift the paradigm for the field and, in so doing, help achieve the long-term goal. The investigators' research areas should form synergistic themes such as studying marine biogeochemical cycles from multiple perspectives, developing computational models that span from intracellular and microscale phenomena to global scales, and studying the mutualistic and antagonistic interactions among the different domains of life.

Multidisciplinary team research projects

MMI seeks to overcome conceptual, disciplinary, technological and methodological barriers that currently hinder scientists from understanding nutrient flow in the ocean; from deciphering the genetic and biochemical bases of microbial metabolism, physiology and ecology; and from understanding how microbes and viruses interact with one another and the consequences of these interactions. One grant-making approach that MMI uses to address these goals is to fund multidisciplinary teams, which support collaborations of international scientists with diverse expertise to overcome these challenges using laboratory, field, theory and computational techniques. MMI also supports instrumentation and methods development projects to enable technological and methodological breakthroughs for a particular discipline and at interdisciplinary interfaces. Two examples of this type of grant are provided below:

1. *Linking Chemical, Physical, and Microbiological Processes that Cause Marine Particles to Disappear (November 2015, Woods Hole Oceanographic Institution):*[159] In support of developing a new interdisciplinary understanding of the mechanisms that underlie small-scale chemical, physical and microbiological phenomena that contribute to marine particle consumption, which is critical for improving models of the ocean carbon cycle.
2. *Novel Fine-Scale Insights into Marine Nutrient Flow Via Chemical Fingerprinting and Imaging (November 2015, Research Foundation for the State University of New York):*[160] In support of using a new combination of high-resolution chemical signature analysis and advanced microscopy technologies to track carbon flow at very fine scales among marine microbes, viruses and particles.

Community resources

Since Phase I, MMI has supported community resource projects that fund the creation and sharing of data and the development of tools, methods and infrastructure that are of broad use to the entire research community. This is a small component of the overall initiative relative to the two preceding grant-making approaches. There are approximately 10 community resources funded to date; below are just some examples of this grant-making approach:

1. *IMG-ProPortal: A data discovery environment for Prochlorococcus-related 'omics data:* In support of developing a data discovery environment that will allow researchers from different disciplines to explore and manipulate 'omics data related to the most abundant marine photosynthetic organism, *Prochlorococcus*.

2. *A Pipeline for Sequencing Individual Virus Genomes:* In support of creating novel high-throughput protocols for sequencing the genomes of individual viruses. Protocols will be shared to benefit the virus ecologist scientific community.
3. *Protocols.io:* Online forums for sharing protocols to strengthen the marine microbial ecology research community (ZappyLab, Inc.).

Experimental model systems, instruments, tools and methods

Model systems, such as the mammalian gut bacterium *E. coli* for microbiology and the fruit fly for biomedicine, have been invaluable for deciphering complex biology. For example, by studying fruit flies, scientists gain insight into the inheritance of human traits such as eye color. But in the world of marine microbial ecology, there are very few model systems and associated tools that enable scientists to deeply explore the physiology, biochemistry and ecology of the marine microbes that drive the ocean's elemental cycles, influence greenhouse gas levels and support marine food webs.[161]

In 2015, MMI started supporting scientists, globally and at all career stages, to accelerate the development of experimental model systems (EMS) in marine microbial ecology; 34 EMS grants were awarded. This international endeavor taps into the efforts of more than 100 scientists across 33 institutions with a broad range of expertise to collectively tackle the challenge of developing methods to bring experimental model systems to the ocean. The genetic tools generated in this effort are expected to enable researchers to more easily disrupt the activities of microbial genes to understand how these organisms function in marine ecosystems, and enable researchers to ask scientific questions in ways not currently possible.[162]

Some examples of the EMS grant-making approach are as follows:

1. *Screening marine microeukaryotes for their amenability for genetic tool development (September 2015):* In support of screening laboratory cultures of marine microeukaryotes for the ability to introduce foreign DNA into cells. Twenty-five universities and research institutes serve as primary grantees, with many additional organizations involved as collaborating institutions.
2. *New genetic tools for marine diatoms (September 2015):* In support of developing genetic tools for marine diatoms. Seven research institutes and universities are involved as primary grantees, with contributions from many collaborating institutions as well.
3. *New genetic tools for marine microeukaryotes (September 2015):* In support of developing genetic tools for marine microeukaryotes (i.e., other than diatoms). Two universities serve as primary grantees (again with collaborating researchers).

This grant-making approach also included 10 grants for "instruments, tools and methods," 3 of which were awarded in 2013 prior to the EMS grants and an additional 7 in 2016, after the approach was established. Most of these grants supported the purchase of laboratory and field equipment in support of ongoing research—for example, high-resolution mass spectrometers, environmental sample processors, advanced microscopy, isotope and protein analysis tools. The remaining grants supported the creation of new methods and protocols—for example, to examine the natural stable isotope patterns of microbial proteins; to explore interactions between marine microbes and viruses; to study gene movement between diverse microbes and the genetic evolution of microbial communities.

Appendix B: Detailed methodology

Document and administrative data review

The MMI document and administrative data review mainly involved examining a set of strategic documents (e.g., 2011 MMI reframe), past evaluations and reviews (e.g., 2015 strategic review), documents describing the call for proposal processes, as well as Phase II grants databases and files (i.e., grant proposal, grant summary, grant close and grantee narrative reports). The review of these documents informed the evaluation on several aspects related to the design, implementation and achievements of the initiative.

The documents were uploaded into Atlas.ti, a qualitative data analysis software, and coded using both closed codes (aligned to the evaluation indicators) and open codes (relevant observations that may not have directly aligned to a given indicator). The coded lines of text were then analyzed by indicator, and the evidence was summarized and presented in each respective section of the report for this line of evidence.

Analysis of the Phase II grants database[163]

The Phase II grants database lists all the grants awarded under Phase II, including the following characteristics:

- Grant principal investigator, title, purpose statement, status and amount
- Number and names of co-principal investigators
- Grant-making approach
- Science focus area (nutrient flow; microbial interactions)
- The strategy (or strategies) the grant aligns with
- The 2015 and 2019 time-phased outcomes the grant is expected to help achieve

The grants were broken down by the above characteristics in different ways to address several of the quantitative indicators in the evaluation matrix.

To assess the extent to which generic research outcomes such as development and take up of new knowledge, tools and models were covered by the Phase II portfolio, the specific scientific time-phased outcomes were first mapped against the generic research outcomes included in the logic model. This was done separately for the 2012–2015 and 2015–2019 time windows. The 2012–2015 outcomes *"management adapts; sum greater than parts"* and the 2015–2019 outcome *"researchers recognized, get follow on funds"* contained in the logic model were not included in the analysis of this line of evidence as they do not relate to scientific content. Moreover, the time-phased outcomes 6 and 8 were not considered as they were discontinued by the program in 2015.

Bibliometric analysis

The metadata of peer-reviewed publications (e.g., journal name, title/abstract/keywords, year of publication, author names/addresses, acknowledgements, references) enabled the quantification of many aspects of MMI's intervention logic using bibliometric methods.

Using the metadata of publications that convey information about the subject of the research they disclose (e.g., journal name and title/abstract/keywords) shed light on the first evaluation question (EQ1), which pertains to the initiative's design and implementation: *In what ways are the initiative's strategies aligned with the current needs of the field?* By studying the structure and dynamics of the field of marine microbiology, at the level of broad topics and finer-grain subfields, it was possible to assess whether MMI-supported publications are concentrated in those topics/subfields that are expanding the most rapidly at the US and world levels. Subsequently, by comparing the specialization profile of MMI to that of other funders in the field (EQ2), it was possible to document complementarities and redundancies in the funding landscape.

Using the remaining set of metadata on peer-reviewed publications (year of publication, author names/addresses, acknowledgements, references) meant many of MMI's expected outputs/outcomes linked to the creation of new innovative knowledge, as laid out in its logic model, could be quantified. This aimed to address EQ6: *In what ways are the initiative-level outcomes being achieved? In what ways are the strategy-level outcomes being achieved?* In addressing EQ6, the measured outputs/outcomes must be placed in a comparative context to provide supporting evidence on the extent of success achieved under MMI. Two angles were taken to achieve this: a comparative analysis corresponding to EQ2 (*What is the role of MMI in supporting this field in relation to government and other private funders?)* and a longitudinal analysis pertaining to EQ7 (*To what extent can results thus far be reasonably attributed to the MMI interventions?*).

Data embedded in the text fields of publications (i.e., title/abstract/keywords) were also used to identify future opportunities in the realm of marine microbial ecology that may be worth pursuing (EQ10 and EQ11).

Bibliometric indicators presented in the evaluation report are defined below. Please refer to the Bibliometric Analysis Technical Report for a full list of indictors measured.

Number of publications (output): This indicator shows the number of publications for a given entity, calculated using a method called full counting. Using this method, each country or research organization that has at least one researcher on the list of authors for a given paper gets a full count (1 publication) for that paper. For example, if a paper is authored by two researchers with addresses in the UK, one from Spain and one from the US, the paper will be counted once for the UK, once for Spain and once for the US.

Average of relative impact factors: The impact factor (IF) of each journal in a given year is measured by counting the total number of citations received in that year by the papers that appeared in that journal in the previous five years. The IF is then obtained by dividing the total number of received citations by the number of articles that appeared in that journal in the previous five years. To account for the differences in citation practices across disciplines, the IF for a journal in a given year is adjusted relative to the average IF of other journals in the same subfield and year (each journal contributes to the average proportionally to the amount of papers it published in the given year). Every published paper is given the IF score of the journal in which it is published. The average of relative impact factors (ARIF) of a given entity is simply an average of the IF scores of its articles, relativized to the disciplines in which they are published.

The ARIF is normalized to 1, meaning that an entity with an ARIF above 1 publishes in higher-than-average-impact journals, an ARIF below 1 means that the entity publishes in lower-than-average-impact journals, and an ARIF near 1 means that the entity publishes in near-average-impact journals.

Relative citation scores: Counting citations can be used as a proxy for measuring contributions to subsequent knowledge generation; however, because citation practices vary between the disciplines and sub-disciplines of science, simple counting would create unwanted biases in the results. To correct these potential distortions, individual publications are evaluated relative to the average citation rate for publications in the same subfield and published in the same year; the normalization also accounts for the type of publication because review articles are usually more cited and include more references than journal articles. This measure is known as the relative citation (RC) rate and it was not used directly in this study's analyses. Rather, it is instrumental in computing the citation distribution index and highly cited publications presented below.

Citation distribution index: To prepare the citation distribution index (CDI), Science-Metrix divides all publications in a given research area into 10 groups of equal size, or *deciles*, based on their RC scores.[164] The 1st decile contains the 10% of publications with the lowest RC scores; the 10th decile contains the 10% of publications with the highest RC scores. For a given entity, it is expected that the RC scores of its publications will follow the global distribution, with an equal proportion of its publications falling in each of the deciles. The ratio of an entity's proportion of papers falling into each decile to the expected proportion in each decile (10%) is multiplied by a weight (negative weight for deciles 1 through 5, positive for 6 through 10). The weighted scores across deciles are then summed to obtain the entity's CDI score. The CDI ranges from -50 (worst-case scenario; all papers in the 1st decile) to 50 (best-case scenario; all papers in the 10th decile) with 0 representing parity with the world level.

Highly cited publications: Highly cited publications (HCP) are publications that received the highest RCs in their respective field. This indicator is used as a proxy to examine research "excellence" because of the high concentration of citations in this elite group of publications (between 40% to 50% of all citations go to these publications). The 10% most cited publications in the database ($HCP_{10\%}$) are identified using the RC scores of publications. Then the fraction of an entity's papers falling among these highly cited publications can be computed, which gives the $HCP_{10\%}$ score of that entity. The score for this indicator is equivalent to the value obtained for the 10th (or, most highly cited) decile used for the calculation of the CDI.

E-survey

Science-Metrix designed, programmed and administered an electronic survey of principal and co-principal investigators who received an MMI Phase II grant. The survey gathered grantees' perspectives primarily on output and outcome achievement and their attribution to MMI's intervention, as well as on the level of risk of MMI projects and on the relevance of MMI. Most survey questions were optional to maximize survey completion because respondents are more likely to stop completing a questionnaire when they realize they must answer every question. The risk of attrition was higher in this case because the questionnaire had a high number of questions, including several open-ended questions.

As presented in Table 2, the e-survey population was N=193 individuals. Of these, 114 respondents completed the survey (n=114), a response rate of 59%. If we include the 11 respondents who partially completed the survey, the response rate is 65%. The survey findings are generalizable to the entire population with 95% confidence and a margin of error of ±5.89%. If we include the incomplete questionnaires, the margin of error is ±5.22%. The number of respondents varied from one question to the other because of the incomplete questionnaires and because most questions were optional. As a result, the response rate and margin of error also varied from one question to the other.

Table 2 Survey response rate

Population	Completed	Partially completed	Response rate[1]	Confidence level	Margin of error[2]
193	114	11	59.1%	95%	±5.89%

Note: [1] Response rate = number of completed surveys, divided by the total population.
[2] Margin of error calculated for a response distribution of 50% and a 95% confidence level.

The e-survey was administered through the Fluid Surveys platform. Each respondent accessed it through a unique link, which enabled Science-Metrix to track those respondents who accessed and completed the e-survey in real time, to ensure reminders could be targeted. Four email reminders were sent to respondents who had not completed and submitted the e-survey. In addition, two reminders were sent by MMI's senior staff.

Quantitative and qualitative data analyses were undertaken using a combination of tools, which included Fluid Surveys' reporting functions, Atlas.ti and Microsoft Excel. Responses were analyzed by evaluation question and are presented accordingly in this report. The survey questions are provided as figure titles, for reference. Throughout the report, N refers either to the total survey population or the number of respondents to a given question; n refers either to the total number of respondents to the survey or the number of respondents who chose a specific option under a given question.

For ease of reading, the following ordinal scale has been used in place of percentages (percentages and counts are provided in brackets) throughout the report.

Table 3 Ordinal scale used for the presentation of the survey results

Points on the Scale	Ordinal Scale	Response Count Range
1	Few	The shared views, opinions or experiences of ≤ 10% of the respondents
2	Some	The shared views, opinions or experiences of 11% ≤ 25% of the respondents
3	Many	The shared views, opinions or experiences of 26% ≤45% of the respondents
4	About Half	The shared views, opinions or experiences of 46% ≤55% of the respondents
5	A majority	The shared views, opinions or experiences of 56% ≤75% of the respondents
6	Most	The shared views, opinions or experiences of 76% ≤90% of the respondents
7	Almost All	The shared views, opinions or experiences of >90% of the respondents

Interviews with internal stakeholders

A draft interview guide was developed based on the evaluation plan as reflected in the evaluation matrix, which matches evaluation questions to the six lines of evidence. The draft interview guide was reviewed by the Moore Foundation Measurement, Evaluation and Learning (MEL) staff and then revised.

Six people involved with aspects of the design and implementation of the MMI program were identified in consultation with the MEL staff. Four in-person interviews of one to one and a half hours were completed at the Moore Foundation in Palo Alto in late July 2017. Two more interviews of 30 minutes and one hour were completed by phone in August 2017.

Grantee consultation and site visits

A draft interview guide was reviewed by the MEL staff and the MMI Program Director and then revised. The guide was designed to be in line with the focal evaluation questions about (1) the design and implementation of the MMI strategies, (2) achievement of expected outcomes, and (3) potential paths forward, following the indicators in the evaluation matrix.

The data for this line of evidence were collected from late August 2017 to early September 2017. Site visits were conducted on both the east and west coasts of the United States. Interviews were conducted with 21 principal and co-principal investigators at 6 different organizations. Of the 21 interviews, 18 were principal investigators and 3 were co-principal investigators. Interview guides were provided to confirmed interviewees in advance, so they could prepare. Three of the interviews were conducted by Skype and two were conducted by telephone due to the remote location of some principal investigators. Laboratory site visits were not conducted for the Skype or telephone interviews. The remaining 16 interviews were conducted in-person. All the interviews were completed in approximately 60–90 minutes, and with the consent of the interviewees all the interviews were digitally recorded.

All four grant-making approaches were covered by the sample of 29 grants: 3 community resources awards (10% of the sample), 4 experimental model systems awards and 3 for development or purchase of new instruments and tools (24% of the sample), 9 investigator awards (31%), and 10 multidisciplinary team research awards (35%). It should be noted that some principal investigators had been awarded more than one grant.

The collected and recorded data were then transcribed. Once transcribed, the interview recordings were destroyed. The transcribed interviews were then uploaded into Atlas.ti, a qualitative data analysis software platform, and transcripts assigned an identifying code to protect the confidentiality of the interviewee. Atlas.ti was used to code and analyze the interview data using both deductive and inductive approaches. First, a closed coding structure was developed based on the evaluation questions and indicators presented in the evaluation matrix. Open coding was only used when unforeseen topics of interest were identified.

Expert panel

An independent international panel of seven external experts was convened by the Moore Foundation to appraise MMI progress toward outcomes, achievements and future opportunities. The panel was chaired by Dr. James Tiedje, who worked with foundation staff to select the other panel members. Dr. Tiedje was also one of five strategic advisors to the evaluation team, and thus was able to provide the other expert panel members with useful insight into the findings of the various lines of evidence.

The panel was asked to evaluate MMI over the second phase of funding (2011–2019), concentrating on the 2015–2019 period and the eight goals to be accomplished by 2019. Panel members were provided with a summary document of the MMI program background, a summary of the recent accomplishments of each of the funded projects, six appendices that provided more detailed information on the projects, and Science-Metrix' bibliometric analysis and grantee survey technical reports. The panel met at the Moore Foundation offices to discuss their findings and arrive at a consensus report. This report was organized according to the three topic areas for which their comments were requested. They reported on the scientific achievements including the 2019 overall goal, followed by the eight TPOs; they also addressed three additional questions posed by the foundation staff.

Appendix C: Evaluation matrix

EQ#	Evaluation Focal Questions	Evaluation Indicators	Lines of evidence: Document and admin. data review	Bibliometric research and literature review	E-survey of PIs/Co-PIs	MMI internal stakeholder interviews	Grantee consultations and site visits	Expert panel
Initiative Design and Implementation								
EQ1	In what ways are the initiative's strategies aligned with the current needs of the field?	1.1 Extent to which the initiative's strategies were based on valid and reliable needs analysis data from marine microbiology community and other potential users of the research	•		•	•		•
		1.2 What areas are growing in marine microbiology and to what extent is MMI research focused in those growth areas relative to the world?		•				•
		1.3 To what extent has past MMI (Phase I and II) research contributed to growing areas in marine microbiology?		•				•
		1.4 Expert opinion on relevance of MMI research to current needs of the field						•
		1.5 Is the MMI 2019 goal (i.e., "constrained outcome") an appropriate aspirational goal for the Initiative and are the time-phased sub goals important ones on the path to achieving the overall 2019 goal?						•

EQ#	Evaluation Focal Questions	Evaluation Indicators	Lines of evidence					
			Document and admin. data review	Bibliometric research and literature review	E-survey of PIs/Co-PIs	MMI internal stakeholder interviews	Grantee consultations and site visits	Expert panel
EQ2	What is the role of MMI in supporting this field in relation to government and other private funders?	2.1 Presence/absence of duplication, overlap and/or complementarity in roles	•		•	•	•	•
		2.2 Comparative analysis of MMI's contribution relative to other world leading organizations and researchers		•				
		2.3 Comparative analysis of MMI's contribution relative to other funders		•				
		2.4 Expert opinion on the role of MMI in the field						•
EQ3	How effective have MMI's grant-making approaches been relative to one another?	3.1 Proportion and importance of single investigator award contributions to MMI outcomes	•		•	•	•	•
		3.2 of multidisciplinary team research contributions, including convening activities	•		•	•	•	•
		3.3 of community resource project contributions	•		•	•	•	•
		3.4 of experimental model system project contributions	•		•	•	•	•
		3.5 Effectiveness of the selection and structure of projects, including role of MMI, the quality of researchers chosen, quality of research approach and sufficiency of resources applied, and scientific and technical progress made						•
EQ4	How effective have MMI's strategies been relative to one another?	4.1 Observed MMI processes and selected MMI projects that show the MMI desired research process characteristics as per the logic model, including convening the marine microbiology community.	•		•	•	•	

EQ#	Evaluation Focal Questions	Evaluation Indicators	Lines of evidence: Document and admin. data review	Bibliometric research and literature review	E-survey of PIs/Co-PIs	MMI internal stakeholder interviews	Grantee consultations and site visits	Expert panel
		4.2 Extent to which MMI selection and support for projects, including overcoming interdisciplinary barriers, are identified as a key success factor	●		●	●	●	●
		4.3 Extent to which developing new technologies, methods, computational modeling techniques, and theory is a key success factor	●		●	●	●	●
		4.4 Extent to which broader adoption of genetically manipulable experimental model systems is a key success factor	●		●	●	●	●
		4.5 Appropriateness of the balance of emphasis across the strategies given the current context and the role of MMI plays the field						●
		4.6 Extent to which the MMI strategies (portfolio effect), approach and management have led to science outputs and outcomes that are greater than the sum of its parts						●
EQ5	What types of risk (structure of science, conceptual, methods, technology) has MMI taken in its interventions? How could MMI consider risk in potential future interventions?	5.1 Evidence/cases of purposive risk-taking (and possibly the learning that came from failure)			●	●	●	
		5.2 Degree and type of risk-taking identified			●	●	●	
		5.3 Positive/negative consequences of risk-taking			●	●	●	
		5.4 Expert opinion on the degree and appropriateness of purposive risk-taking						●

EQ#	Evaluation Focal Questions	Evaluation Indicators	Lines of evidence					
			Document and admin. data review	Bibliometric research and literature review	E-survey of PIs/Co-PIs	MMI internal stakeholder interviews	Grantee consultations and site visits	Expert panel
Achievements								
EQ6	In what ways are the initiative-level scientific and technical outcomes being achieved? In what ways are the strategy-level outcomes being achieved?	6.1 Extent to which the outputs in logic model have been achieved	•	•	•		•	
		6.2 Extent to which the 2012–2015 and ongoing outcomes in the logic model have been achieved	•	•	•		•	•
		6.3 Extent to which the 2015–2019 logic model outcomes have been achieved	•		•		•	•
		6.4 Extent to which field has shifted toward a greater emphasis on studying microbial interactions and nutrient flow	•	•			•	•
		6.5 Extent to which the time-phased outcomes required towards establishing a new paradigm for the field of marine microbiology have been achieved	•				•	•
		6.6 Expert opinion on scientific progress and initiative level outcome achievement, including an assessment on the timescale to be expected for achieving MMI sub goals and 2019 aspirational goal.						•
EQ7	To what extent can results thus far be reasonably attributed to the MMI interventions (strategies, approaches, grants, workshops, and other program	7.1 Proportion and importance of grant-making interventions to MMI outcome achievements	•		•		•	
		7.2 Proportion and importance of non-grant-making interventions to MMI outcome achievements	•		•		•	
		7.3 Proportion and importance of other funder interventions	•		•		•	

EQ#	Evaluation Focal Questions	Evaluation Indicators	Lines of evidence					
			Document and admin. data review	Bibliometric research and literature review	E-survey of PIs/Co-PIs	MMI internal stakeholder interviews	Grantee consultations and site visits	Expert panel
	efforts)?	and other external influences to MMI outcome achievements						
		7.4 Longitudinal analysis of MMI's effect on the field		•				
		7.5 Expert opinion on extent to which MMI has contributed to observed outcomes and to the field						•
EQ8	What unintended consequences (positive and negative) have resulted from MMI's interventions?	8.1 Evidence/cases of positive unexpected outcomes attributable to MMI interventions	•		•	•	•	•
		8.2 Evidence/cases of negative unexpected outcomes attributable to MMI interventions	•		•	•	•	•
EQ9	What challenges has MMI encountered, and what adaptations have been made as a result of these challenges? What are the most significant lessons learned?	9.1 Evidence/cases of challenges encountered	•		•	•	•	
		9.2 Evidence/cases of adaptations/adjustments	•		•	•	•	
		9.3 Evidence/cases of lessons learned	•		•	•	•	
Potential Path Forward								
EQ10	Are there future opportunities in the realm of marine microbial ecology that may be worth pursuing by MMI? What are the relative strategic and scientific risks and potential gains of those opportunities?	10.1 Emergence of entirely new fields of scientific inquiry at the interface of existing topics in marine microbial ecology and related disciplines		•	•	•	•	•
		10.2 Expert opinion on relative strategic and scientific risks and potential gains of those opportunities						•

EQ#	Evaluation Focal Questions	Evaluation Indicators	Lines of evidence					
			Document and admin. data review	Bibliometric research and literature review	E-survey of PIs/Co-PIs	MMI internal stakeholder interviews	Grantee consultations and site visits	Expert panel
EQ11	How would MMI's work to date inform and shape these potential future opportunities?	11.1 Degree of flexibility and risk tolerance in selection of emerging research topics given where MMI investments are now	●		●	●	●	●
		11.2 Comparative analysis of extent to which MMI research is contributing to emerging topics/fields in marine microbiology and related disciplines (publications) (see points 2.2 and 2.3).		●				●
		11.3 Comparative analysis of extent to which past MMI research has contributed to emerging topics/fields and related disciplines (citations) (see points 2.2 and 2.3).		●				●
		11.4 Expert opinion the most promising research opportunities for MMI in marine microbial ecology and related disciplines to build on MMI strengths						●
		11.5 Expert opinion on how best to find and form and projects in these emerging areas						●

Appendix D: MMI theory of change and logic model

During the planning phase for this evaluation, a preliminary logic model was developed to reflect the MMI theory of change based on the available information. It was revised with MEL and MMI input and further refined as data collection proceeded (Figure 8). It adheres to standard principles and characteristics of logic modeling and is proposed here along with the accompanying narrative below as the key reference document for understanding the MMI theory of change and assessing outcome achievement.

The logic model is a plausible and simplified depiction of how MMI may work under certain conditions to solve identified challenges. It shows how inputs, activities and outputs are expected to lead to short-, medium- and long-term outcomes. As noted throughout the evaluation report, there is a great deal of overlap and synergy among the three strategies and four grant-making areas of the MMI portfolio, so the logic model does not attempt to show separate outputs for each strategy and funding area. Similarly, outcomes reflect the general pattern of achievements in the shorter run and take up of these by researchers outside the program in the medium and long term, including for many years after the initiative's currently scheduled end in 2019. The time frames assigned to outcomes in the logic model followed those of MMI's time-phased outcomes and enabled the evaluation to set expectations in terms of the types and extent of outcome achievement that could be observed during the evaluation period. A narrative of the theory of change is provided below, describing Figure 8 from left to right.

MMI inputs include the Moore Foundation's vision, strategies and direction, MMI plans, funds, expertise of staff and advisors, partnerships and leveraged resources.

MMI activities include program design and implementation and the four MMI portfolio areas: fund individual researchers, fund multidisciplinary teams, fund community resources, and fund (genetics-enabled) experimental model systems. The design and implementation activity also includes the strategy of supporting interdisciplinary research, and one way this is done is by convening diverse groups of researchers.

Research process characteristics were expected to be key to the success of the MMI program. These characteristics can be thought of as a unique MMI approach to research management. This MMI management approach is described as flexible and adaptive, promoting interactions of the marine microbiology community to stimulate cross-fertilization, collaboration and idea exchange. Funding is expected to enable awardees to take on higher-risk projects and to address synergistic themes as they see fit. Instrumentation, methods, tools and data sets are being funded to fill marine microbiology knowledge gaps. Other characteristics include aspects of interdisciplinarity and collaboration among diverse and complementary scientific perspectives. A variety of research approaches are encouraged, including use of lab, field, theory and computational models and experimental model systems.

Outputs include the usual plans, grants and workshops/events. There are also four broad categories of outputs: partnerships; advancements in knowledge; advancements in tools, methods, models, and technologies (particularly measurement technologies); and new genetics tools. These outputs are expected in key focus areas of microbial interactions and flow of nutrients.

Shorter-term outcomes (2012–2015 and ongoing) are that the further development, testing and validation of new methods, tools and techniques ought to be observed. In addition, there may be reaction, uptake and use of these outputs by the research community, and the presence of characteristics that fuel that uptake. For example, new knowledge is used and cited in others' research, improved computational models will address the complexity of the system better than earlier models, and measurement tools will have better functionality—such as range, depth or resolution—than the tools they replace. Tests of experimental model systems will demonstrate their functionality. At this point and into the near future, examples may be observed of management adding value and adapting to challenges and changes.

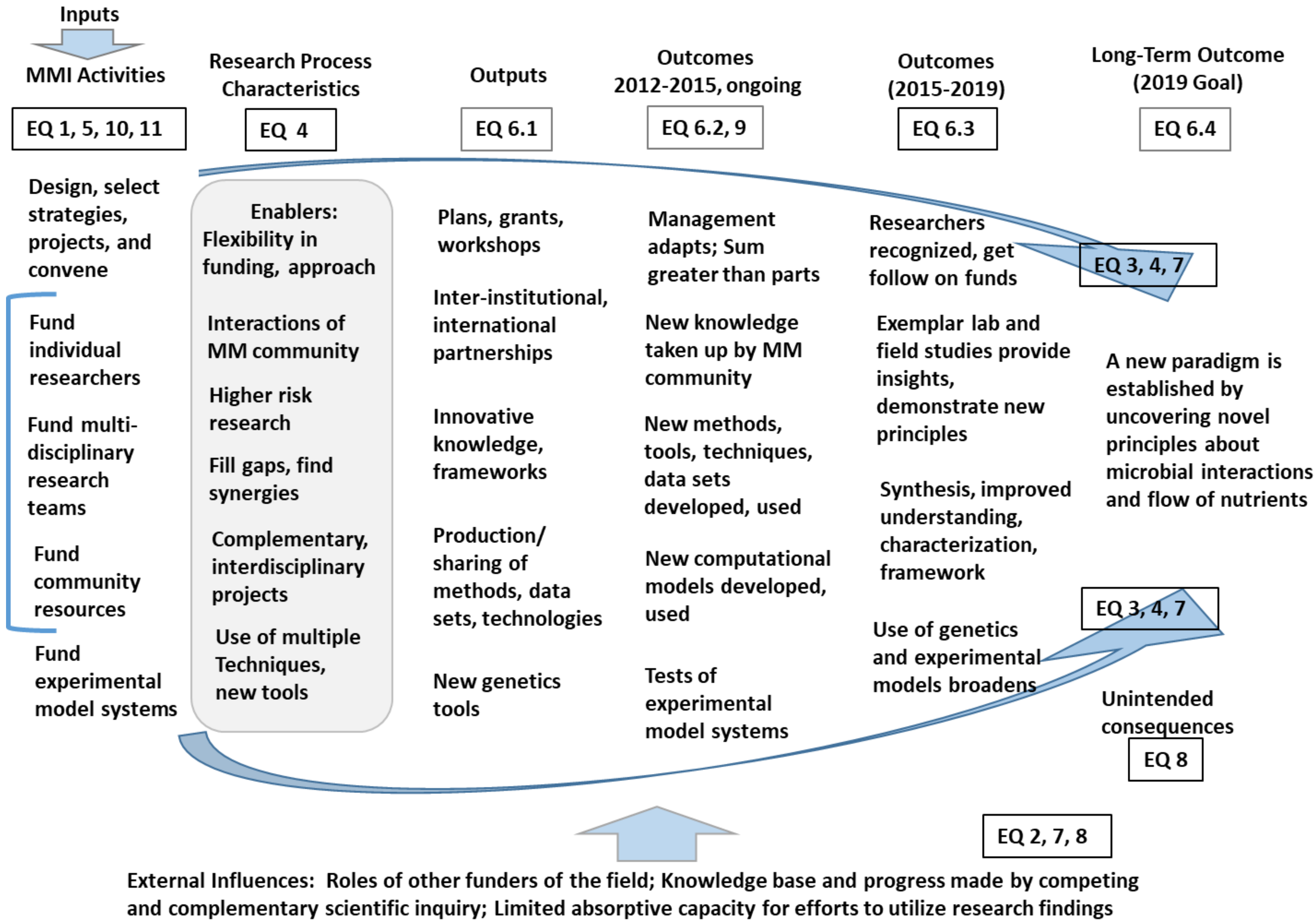
Medium-term outcomes (2015–2019) here summarize contributions to the field and movement of the portfolio of projects toward the 2019 goal. The general areas reflect the individual 2019 goals, which result from application of the methods, tools and techniques developed earlier through MMI support (and by others). These are exemplar lab and field studies to provide insight and demonstrate new scientific principles; synthesize an improved understanding, characterization of underlying principles, and conceptual framework; and broader use of genetics and experimental model systems. For the design strategy, it is expected that MMI researchers will be recognized as leaders in their field and will be able to attract additional outside funding for their research.

Long-term outcome (2019 goal): As the logic model shows graphically, all MMI efforts, in particular the medium-term outcomes, are aimed at achieving the long-term outcome, which corresponds to the MMI 2019 goal:

> "*A new paradigm will be established by uncovering the underlying principles that govern inter- and intra-domain microbial interactions and that influence the flow of nutrients in representative marine microbial ecosystems.*"

External influences are also an integral part of this logic model, presented at the bottom of the graphic. The presence and extent of influence MMI's funding of research and research management approach have on output and outcome achievement is indicative of the effectiveness of MMI. However, non-program influences play a large role as well. Assessing the contribution of MMI to observed outcomes, including the part that program design played in that contribution, requires investigating other plausible explanations or external influencers for the observed outcomes.

Figure 8 Logic model of the Marine Microbiology Initiative (MMI)



Source: Prepared by Science-Metrix for the evaluation of MMI Phase II

Appendix E: MMI time-phased outcomes

Table 4 2015 and 2019 time-phased outcomes

2015 outcomes	2019 outcomes
1. Tools exist to measure a basic suite of microbial interactions.	1. Exemplar laboratory and field investigations of microbial interactions demonstrate their importance in understanding ecosystem processes.
2. Strategic plans are developed and experiments initiated to investigate 2–3 experimental model systems.	2. Experimental model systems for probing microbe–microbe interactions and nutrient flow enable generation of new ecological and evolutionary hypotheses for ocean investigation.
3A. A computational ecosystem model includes at least: virus–host interactions, microbe–microbe signaling, organic matter and/or predator-prey interactions. 3B. New approaches to ecosystem models are established.	3. Computational models accommodate the complexity of microbial interactions and nutrient flow in the ocean.
4A. Incorporation of specific nutrients into single cells can be measured, including using high throughput techniques. 4B. Microbial interactions can be measured at the single-cell level.	4. Exemplar laboratory and field investigations at the single-cell level reveal mechanistic understanding of microbial interactions and nutrient flow.
5. Tools exist to taxonomically resolve geochemical pathways.	5. Exemplar field investigations of geochemical pathways (including the rates of geochemical transformations) use finely resolved taxonomic information to provide new insights into nutrient flow.
6A. A robust comparison of metatranscriptomic, metaproteomic and microchip approaches is made. 6B. Advance microchip devices enable measuring multiple metabolic pathways.	Objective discontinued in 2015.
7A. New hypotheses and theories exist for how to scale from cellular measurements to ecosystem. 7B. Understanding of microscale processes developed in the lab, are field tested.	7. A conceptual framework exists to infer ecosystem scale processes from microscale measurements.
8. Rates of processes can be predicted from expression levels of certain genes.	Objective discontinued in 2015.
9A. Microbial interactions are placed into a phylogenetic context to further understanding of co-evolutionary processes. 9B. The evolutionary history of organisms involved in nutrient flow is routinely studied.	9. Exemplar laboratory and field investigations of evolutionary processes and mechanisms demonstrate the importance of placing microbial interactions and nutrient flow in an evolutionary framework.
10. Tools and informatics resources exist to allow researchers to analyze and compare organic matter profiles at the molecular scale.	10. Exemplar laboratory and field investigations integrate highly resolved organic matter composition and microbial analyses to understand organic matter cycling.

Source: 2015 Marine Microbiology Initiative internal strategic review

Appendix F: Additional data tables

Using the Phase II grants database, the grants were broken down by grant-making approach and by the 2015 and 2019 outcomes whose achievement they were expected to contribute to, as organized in the logic model. The results of the analysis are presented in Table 5. The preponderance of multidisciplinary team awards and investigator awards is reflected in the contribution of these two grant-making approaches to the logic model outcomes. Multidisciplinary team awards and investigator awards are the predominant contributors to all outcomes, except for outcomes related to genetics models and experimental model systems, which are logically covered by experimental model systems.

Table 5 Coverage of logic model outcomes by grant-making approach

Expected outcomes	Grant-making approach			
	Investigator awards # grants and funding amount	Multidisciplinary teams # grants and funding amount	Community resources # grants and funding amount	Experimental model systems # grants and funding amount
2012–2015 outcomes				
New methods, tools, techniques, data sets developed and used	12 $23,080,000	16 $23,636,549	1 $764,517	3 $2,168,754
Tests of experimental model systems	2 $3,237,000	2 $3,312,594	0 $0	34 $8,159,378
New computational models developed, used	4 $6,463,000	4 $5,671,900	0 $0	0 $0
New knowledge, taken up by marine microbiology community	12 $21,929,000	13 $21,458,682	2 $842,259	3 $2,552,568
2015–2019 outcomes				
Exemplar lab and field studies provide insights, demonstrate new principles	13 $25,241,000	20 $29,748,076	6 $2,568,308	9 $6,451,046
Synthesis, improved understanding, characterization, framework	14 $21,583,000	20 $30,060,729	4 $1,429,791	43 $14,610,424
Use of genetics and experimental models broadens	1 $1,553,000	5 $9,286,963	2 $587,532	34 $8,159,378

Note: A single grant can address several logic model outcomes for a given phase (e.g., 2012–2015 or 2015–2019) but can be classified in only one grant-making approach. Thus, the total of grants by Time-phased outcome might be higher than the total of grants allocated.

Source: Compiled by Science-Metrix using the MMI Phase I and II Grants database

As part of this evaluation an expert panel was convened to appraise MMI progress toward outcomes. The panel members rated progress for each time-phased outcome (TPO), citing examples of MMI principal investigators (PIs) whose projects contributed to each TPO. The evaluation team mapped each PI cited by the panel to the type of grant awarded, where A= individual investigator awards, B = multidisciplinary teams, C= community resource projects and D= experimental model systems.

Table 6 Achievement as assessed by the expert panel

2015–2019 Time Phased Outcomes (Goals)	Level of Progress Achieved	Contributing Grant-Making Approaches (# PIs cited)
1. Exemplar laboratory and field investigations of microbial interactions demonstrate their importance in understanding ecosystem processes.	Excellent progress	A (1) B (5) D (1)
2. Experimental model systems for probing microbe–microbe interactions and nutrient flow enable generation of new ecological and evolutionary hypotheses for ocean investigation.	Excellent progress	A (2) B (3) D "Primarily EMS", specific PIs not cited
3. Computational models accommodate the complexity of microbial interactions and nutrient flow in the ocean.	Very good progress	A (4) B (1)
4. Exemplar laboratory and field investigations at the single-cell level reveal mechanistic understanding of microbial interactions and nutrient flow.	Excellent progress	A (1) B (4)
5. Exemplar field investigations of geochemical pathways (including the rates of geochemical transformations) use finely resolved taxonomic information to provide new insights into nutrient flow.	Very good progress	A (1) B (4)
6. Routine use of proxies, such as molecular probes, enables researchers to obtain a comprehensive view of the complexity of multiple pathways in ocean processes.	Discontinued	N/A
7. A conceptual framework exists to infer ecosystem scale processes from microscale measurements.	Good progress	A (4) B (3)
8. Rates of processes can be determined from molecular measurements (e.g., DNA, RNA, proteins).	Discontinued	N/A
9. Exemplar laboratory and field investigations of evolutionary processes and mechanisms demonstrate the importance of placing microbial interactions and nutrient flow in an evolutionary framework.	Good progress	A (2) B (2)
10. Exemplar laboratory and field investigations integrate highly resolved organic matter composition and microbial analyses to understand organic matter cycling.	Very good to excellent progress	A (3) B (3)

Source: Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation

Table 7 Analysis of award distribution

Number and share of Phase II grantees that received support in Phase I

	A			B			C			D			Total		
	#	%	% of funding	#	%	% of funding	#	%	% of funding	#	%	% of funding	#	%	% of funding
Phase II grantees	17	-	-	57	-	-	12	-	-	139	-	-	199	-	-
Phase II grantees that received Phase I support	11	64.7%	62.1%	10	17.5%	27.9%	1	8.3%	6.2%	10	7.2%	13.3%	22	11.1%	36.4%
Phase II PIs that received Phase I support	11	64.7%	62.1%	6	10.5%	25.4%	1	8.3%	6.2%	5	3.6%	9.6%	18	9.0%	34.6%
Phase II Co-PIs that received Phase I support	0	0.0%	0.0%	4	7.0%	2.5%	0	0.0%	0.0%	5	3.6%	3.4%	0	0.0%	1.7%

Note: A grantee is considered a PI for a given period if they appear as the PI on at least one grant for the period. For example, a grantee who is PI on one grant and Co-PI on another in Phase II is considered to be a PI for that period. The % of funding allocated to a given group of grantees is expressed as the share of the funding allocated to each grant-making approach. Grantees are only counted once, regardless of the number of grants on which they appear. Funding on a grant has been equally fractioned across grantees.
Source: Computed by Science-Metrix using data from MMI Phase I and II grants database

Number and share of Phase II grantees that received multiple grants combining Phase I and Phase II grants

	A			B			C			D			Total		
	#	%	% of funding	#	%	% of funding	#	%	% of funding	#	%	% of funding	#	%	% of funding
Phase II grantees	17	-	-	57	-	-	12	-	-	139	-	-	199	-	-
Phase II grantees overall	14	82.4%	84.8%	20	35.1%	50.5%	5	41.7%	53.0%	23	16.5%	30.8%	41	20.6%	58.9%
Phase II PIs	14	82.4%	84.8%	17	29.8%	44.0%	5	41.7%	53.0%	17	12.2%	24.3%	33	16.6%	55.0%
Phase II Co-PIs	0	0.0%	0.0%	3	5.3%	6.5%	0	0.0%	0.0%	6	4.3%	6.6%	8	4.0%	3.9%

Note: A grantee is considered a PI for a given period if they appear as the PI on at least one grant for the period. For example, a grantee who is PI on one grant and Co-PI on another in Phase II is considered to be a PI for that period. The % of funding allocated to a given group of grantees is expressed as the share of the funding allocated to each grant-making approach. Grantees are only counted once, regardless of the number of grants on which they appear. Funding on a grant has been equally fractioned across grantees.
Source: Computed by Science-Metrix using data from MMI Phase I and II grants database

Number and share of Phase II grantees that received multiple grants in Phase II

	A			B			C			D			Total		
	#	%	% of funding	#	%	% of funding	#	%	% of funding	#	%	% of funding	#	%	% of funding
Phase II grantees	17	-	-	57	-	-	12	-	-	139	-	-	199	-	-
Grantees overall	11	64.7%	68.6%	16	28.1%	42.1%	4	33.3%	46.8%	18	12.9%	23.2%	28	14.1%	47.9%
PIs	11	64.7%	68.6%	14	24.6%	38.0%	4	33.3%	46.8%	15	10.8%	20.3%	13	6.5%	25.7%
Co-PIs	0	0.0%	0.0%	2	3.5%	4.1%	0	0.0%	0.0%	3	2.2%	2.9%	8	4.0%	6.7%

Note: A grantee is considered a PI for a given period if they appear as the PI on at least one grant for the period. For example, a grantee who is PI on one grant and Co-PI on another in Phase II is considered to be a PI for that period. The % of funding allocated to a given group of grantees is expressed as the share of the funding allocated to each grant-making approach. Grantees are only counted once, regardless of the number of grants on which they appear. Funding on a grant has been equally fractioned across grantees.
Source: Computed by Science-Metrix using data from MMI Phase I and II grants database

Table 8 Suggestions for potential future areas of MMI inquiry

Line of evidence	Suggestion
Bibliometric analysis	The analysis identified the following emerging topics in marine microbiology: functional gene abundance, the Community Earth System Model (CESM), marine microplastics, next-generation sequencing, virus-bacteria interactions.[165]
E-survey of MMI grantees	83 responses for suggested future opportunities and focus areas were provided by survey respondents. It was not within the scope of the evaluation to analyze or group these responses into categories. Individual responses were included in Appendix D of the survey technical report sent to the Moore Foundation during this evaluation.
Interviews with internal stakeholders	Gap analysis by MMI staff pinpointed a few broad focus areas such as exploring chemical drivers in the ocean and continued investment in genetic tools and EMS.[166]
Grantee consultation and site visits	Some grantees identified the need for further investments in cellular and molecular physiology to better understand the continuum of life from plant to animal, and related mixotrophic and symbiotic behaviors across different taxa of marine organisms. Ocean connectivity was also touched upon by most of the grantees, particularly as it relates to ecosystem modeling and its prerequisites.[167]

Source: Compiled by Science-Metrix

Appendix G: References

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[4] Chandler, "2011 Marine Microbiology Initiative Strategy Update and Request for Reframe Allocation," 2.

[5] Vicki Chandler and Ajit Subramaniam, "2014 Marine Microbiology Initiative Allocation Request," 2014.

[6] Gordon and Betty Moore Foundation, "Request for Expressions of Interest: Increasing the Potential of Marine Microeukaryotes as Experimental Model Systems through the Development of Genetic Tools," November 21, 2014.

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[8] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," Technical Report (Montreal, Canada, September 20, 2017), 4–5.

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[10] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," Technical Report (Montreal, Canada, September 27, 2017), 12.

[11] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Document and Administrative Review," Technical Report (Montreal, Canada, September 1, 2017), 2.

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[13] Jon Kaye et al., "2015 Marine Microbiology Initiative Strategy Review," 2015.

[14] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," 12.

[15] Science-Metrix, 19.

16 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," Technical Report (Montreal, Canada, October 2, 2017), 4.

17 James Tiedje et al., "Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation," October 6, 2017, 11.

18 Tiedje et al., 1.

19 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 5.

20 Jon Kaye, "Grant Development Instructions for Successful Applicants," 2012, 1.

21 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 5.

22 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - E-Survey," 8.

23 Science-Metrix, 24.

24 Tiedje et al., "Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation," 13.

25 In this context, "largest" refers to the number of research publications supported by each funder.

26 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," 34.

27 Differences in scores for the Moore Foundation (referred to as GBMF in table) as a funder and MMI Phase II are due to differences in approach to identifying the publications in each set. Comparing MMI with other funders required using the same search strategy to ensure an accurate comparison. Funders (including MMI) were identified through searches in the funding acknowledgements of papers. Most papers acknowledging GBMF did not specify the initiative (e.g., MMI) through which they were funded. As most papers acknowledging GBMF that fall within the marine microbiology data set were likely supported through MMI, a GBMF data set was created by searching exclusively through the funding acknowledgements section of papers for more accurate comparison to other funders; a list of supported publications such as the one provided by MMI was not readily available for other funders in the field.

28 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," 34.

29 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Document and Administrative Review," 10.

30 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," 35.

[31] Science-Metrix, 112.

[32] Science-Metrix, 35, Table 19.

[33] Science-Metrix, 35, 36, Table 22, 23.

[34] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 5.

[35] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 5.

[36] Science-Metrix, 5–6.

[37] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Document and Administrative Review," 11.

[38] Kaye et al., "2015 Marine Microbiology Initiative Strategy Review," 2,3.

[39] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 2.

[40] Science-Metrix, 7.

[41] Tiedje et al., "Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation," 10.

[42] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 6.

[43] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," 52.

[44] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - E-Survey," 24.

[45] Similarly, very few EMS grants were considered in the bibliometric analysis as the majority were granted after 2015.

[46] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Document and Administrative Review," 22.

[47] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 9.

[48] Science-Metrix, 9, 10.

[49] Science-Metrix, 10.

[50] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 6,7,11.

[51] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - E-Survey," 14.

[52] Science-Metrix, 5.

[53] Science-Metrix, 11.

[54] Science-Metrix, 11.

[55] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 6.

[56] Tiedje et al., "Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation," 1.

[57] Tamás Vasvári, "Risk, Risk Perception, Risk Management–a Review of the Literature," *Public Finance Quarterly* 1 (2015): 29.

[58] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 13.

[59] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - E-Survey," 8.

[60] Science-Metrix, 8.

[61] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 13.

[62] Tiedje et al., "Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation," 5.

[63] Tiedje et al., 4.

[64] Vasvári, "Risk, Risk Perception, Risk Management–a Review of the Literature," 38.

[65] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 11.

[66] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 13.

[67] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 11–12.

[68] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 13.

[69] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 11.

[70] Tiedje et al., "Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation," 3–4.

[71] Tiedje et al., 4.

[72] Tiedje et al., 8.

[73] Tiedje et al., 6.

[74] Tiedje et al., 5.

[75] Tiedje et al., 6.

[76] Tiedje et al., 7.

[77] Tiedje et al., 7.

[78] Tiedje et al., 11.

[79] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," 35.

[80] Science-Metrix, 44, Table 21.

[81] Science-Metrix, 36, Table 22, 23.

[82] Tiedje et al., "Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation," 2.

[83] Kaye et al., "2015 Marine Microbiology Initiative Strategy Review," sec. Appendix 3.

[84] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," 23.

[85] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 14.

[86] Science-Metrix, 15.

[87] Science-Metrix, 17.

88 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Document and Administrative Review," 29.

89 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 18.

90 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - E-Survey," 24.

91 Science-Metrix, fig. 30.

92 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 20.

93 Tiedje et al., "Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation," 10.

94 Kaye et al., "2015 Marine Microbiology Initiative Strategy Review."

95 "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 16.

96 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 21.

97 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Document and Administrative Review," 17–19.

98 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 20.

99 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - E-Survey," 12.

100 Science-Metrix, 10.

101 Kaye, "Grant Development Instructions for Successful Applicants," 1.

102 Kaye, 2.

103 Kaye, 2.

104 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Document and Administrative Review," 16–17.

105 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 7, 18.

106 Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 5.

[107] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 7.

[108] Tiedje et al., "Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation," 10.

[109] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," 52.

[110] Science-Metrix, fig. 27.

[111] Tiedje et al., "Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation," 9.

[112] Kaye et al., "2015 Marine Microbiology Initiative Strategy Review," 6.

[113] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," sec. addendum on unexpected outcomes.

[114] The White House Office of Science and Technology Policy, "Fact Sheet: Announcing the National Microbiome Initiative," Press release, May 13, 2016, 9, https://obamawhitehouse.archives.gov/sites/whitehouse.gov/files/documents/OSTP%20National%20Microbiome%20Initiative%20Fact%20Sheet.pdf.

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[124] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 6.

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[128] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," 68.

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[130] American Association for the Advancement of Science, "2012 External Review of the Marine Microbiology Initiative," 28.

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[132] Science-Metrix, 8.

[133] Tiedje et al., "Marine Microbiology Initiative (MMI) Expert Panel Report to the Gordon and Betty Moore Foundation," 14.

[134] Tiedje et al., 14.

[135] Tiedje et al., 16.

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[139] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Document and Administrative Review," 33.

[140] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," 95.

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[152] Chandler, 2.

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[159] Gordon and Betty Moore Foundation, "1. MMI Phase I and II Grants," 2017.

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https://www.moore.org/article-detail?newsUrlName=$8m-awarded-to-scientists-from-the-gordon-and-betty-moore-foundation-to-accelerate-development-of-experimental-model-systems-in-marine-microbial-ecology.

[162] Gordon and Betty Moore Foundation.

[163] The exact file name is "1. MMI Phase I and II Grants", referred to as the "Phase II grants database" throughout the report, except for chart sources.

[164] Two adjustments are made to ensure high-quality results, and these pertain to (a) cases where a number of publications are tied in their scores, and (b) cases where the total number of publications is not divisible by 10. For the first case, (a), papers tied at the margin of two deciles will be grouped together and then divided proportionately to ensure that each decile contains the right number of papers. In the case of the total number of papers not being divisible by 10, (b), papers will be fractioned to ensure that the deciles are always of exactly equal size.

[165] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Bibliometric Research and Literature Review," 91.

[166] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Internal Interviews," 18.

[167] Science-Metrix, "Evaluation of the Marine Microbiology Initiative. Technical Report - Grantee Consultation and Site Visits," 25.