Broader Impacts of Science on Society

How do scientists impact society in the twenty-first century? Many scientists are increasingly interested in the impact that their research will have on the public. Scientists likewise must answer this question when applying for funding from government agencies, particularly as part of the "Broader Impacts" criterion of proposals to the US National Science Foundation (NSF). This book equips scientists in all disciplines to do just that, by providing an overview of the origins, history, rationale, examples, and case studies of broader impacts, predominantly drawn from the author's experiences over the past five decades. Beyond including theory and evidence, it serves as a "how to" guide of best practices for scientists. Although this book primarily uses examples from NSF, the themes and best practices are applicable to scientists and applications around the world where funding also requires impacts and activities that benefit society.

Bruce J. MacFadden is a Distinguished Professor at the University of Florida. He has written 200 peer-reviewed publications and a book (*Fossil Horses: Systematics, Paleobiology, and Evolution of the Family Equidae*, Cambridge University Press, 1992). He has been Principal Investigator of 50 NSF grants totaling more than $35 million over the past five decades. Professor MacFadden is a Fellow of the American Association for the Advancement of Science, the Geological Society of America, and the Paleontological Society. He was President of the Society of Vertebrate Paleontology (1986–1988) and President of the Paleontological Society (2018–2020). A former NSF Program Officer (2009–2010), he teaches graduate seminars and provides professional development on Broader Impacts.

"MacFadden has led an extensive life in science, as a paleontologist, museum curator, university administrator, and National Science Foundation staff member. His analyses of NSF history and policy changes from the agency's 1952 start through 2018 – and of many successes and challenges of his own – will be invaluable to anyone seeking research funds from this important government entity. The book focuses on explaining NSF's poorly understood Broader Impacts requirement, and it is especially needed now, when in some programs only about one in ten applications to NSF for funding are successful."

– Bruce Alberts, University of California, San Francisco;
former President of the National Academy of Sciences

"An excellent, pragmatic guide to the philosophy and practice of articulating the many dimensions of broader impacts of science on society, from a highly respected and experienced paleontologist and former National Science Foundation Program Officer. Well-written and accessible, this worthwhile book provides clear and useful information and advice on planning, preparing, and executing activities that are motivated by the genuine spirit of achieving a broader societal impact beyond scientific research. As it becomes increasingly important for scientists to communicate more often and more effectively with non-scientists, *Broader Impacts of Science on Society* serves as an invaluable resource to all who seek to extend the reach of their specific scientific insights and expertise to the rest of the world."

– Sandra J. Carlson, University of California, Davis;
Past-President of the Paleontological Society

"An accessible and practical book that models a reflective and informed approach to thinking about the impacts of scientific research on society. Those who design, study and evaluate Broader Impacts, communication, and learning activities will find the examples, anecdotes, and background information very relevant and useful. Having been on many sides of the audience equation, MacFadden provides a holistic guide for enlightened, engaged scholarship and practice of Broader Impacts."

– Jamie Bell, Project Director, Center for Advancement
of Informal Science Education (CAISE)

"This book provides an in-depth look at all aspects of broader impacts. It is a resource for anyone interested in the historical development of Broader Impacts as well as those seeking to understand the complexity of the Broader Impacts criterion and how to effectively address it."

– Susan Renoe, University of Missouri

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Preface

In the classic report *Science: The Endless Frontier*, Vannevar Bush (1945) envisioned the future of US science and technology for the second half of the twentieth century. This report also provided a roadmap for the creation of the National Science Foundation (NSF) in 1950. In a modern context, science, technology, engineering, and mathematics, commonly referred to as "STEM," are in many respects fundamental drivers of globalized nations as they advance in the twenty-first century. Despite the importance of STEM, however, professionals working in these fields have traditionally not done a good job of communicating their knowledge and discoveries outside the comfort zone of their content discipline. This lack of proper communication and dissemination has unfortunate outcomes with respect to both public understanding and support for basic research. This is where Broader Impacts come into focus. Although more context for the notion of Broader Impacts is provided throughout this book, the foundation of this concept is embodied within the desire for relevance to and benefit of science and STEM for society.

The purpose of this book is thus to provide a background, overview, and guide to the range of Broader Impacts and related activities, particularly as these relate to NSF. These themes are intended to serve as examples and best practices for professionals wanting to reach out to society. For reasons that will hopefully become clearer in what follows, two terms are used throughout this book. "**Broader Impacts**" is used in the context of the merit review criteria and activities that one does as part of a project funded by NSF. In contrast, when I use "**societal benefit**," "**benefit society**," or "**benefit to society**," these represent a more inclusive context that encompasses activities that may, or may not, include specific reference to NSF (Inset 0.1). For example, one might develop a personal website that describes their research and outreach activities. In this context, this is an example of outreach for **societal benefit**, with a goal of disseminating knowledge and activities to a large audience. Perhaps this same scientist then submits an NSF proposal for a new research idea; in this case they could repurpose their website as part of a **Broader Impacts** plan within the proposal description.

Science versus STEM

When NSF was founded in 1950, the acronym STEM did not exist; this word has, however, become commonplace in society today (Inset 0.1). As a scientist, I consider myself to be part of STEM. In the chapters of this book, I sometimes use *science* and *STEM* interchangeably. This is similar to the broad use of the term science (e.g., Bush's *Science: The Endless Frontier* [1945], which was meant to also include technology, and if he were writing today, likely STEM). Likewise, the name "National Science Foundation" includes the word science, but in the present-day context this institution encompasses STEM as well. I considered whether "STEM" or "science" should be in the title of this book, and went back and forth several times.

Important words and phrases used in this book

- **STEM**: Science, Technology, Engineering, and Math; term used over the past few decades to include the four words that form the acronym.
- **Science**: Can be used in a more restrictive context to mean only the science in STEM, or in a more inclusive context to include all STEM activities. For example, the activities of the National Science Foundation (NSF) encompass STEM. The words "science" and "scientist" are frequently used in a more inclusive context in this book.
- **Broader Impacts**: Specific activities proposed for NSF projects.
- **Societal benefit**: the goal of scientists who do outreach activities, some of which are supported by NSF, others of which may be done independently.

Inset 0.1

Some of my colleagues, particularly in education, find STEM to be a hackneyed term that may at some point outlive its identity (e.g., STEAM [Art] is trending now). In addition, as the book developed, given my background as a scientist, after Chapter 1 most of the examples that I use come from science. If I had used STEM in the book title it might have misled the reader. In the final analysis, whereas STEM is commonplace now, "science" is a more enduring term that will likely persist, and the latter better identifies the primary focus of this book. Thus, in the pages below, the terms "science" and "scientist" are frequently used to also include the other aspects of STEM.

Audience

When I worked as a program officer at NSF (2009–2010), a colleague taught me that one of the most important things that needs to be understood is to know your intended audience (Chapter 8). While this seems obvious, it is not always understood by scientists. I try to know my audience, not just when writing proposals, but also during classes, academic seminars, publishing peer-reviewed papers, or presenting public talks. Thus, we should be aware of our audiences any time we communicate with them. Audiences can be complex and oftentimes include intersecting subsets of people with different backgrounds and experiences. They are not necessarily homogeneous and invariably include learners with different knowledge. This is the case for this book as well.

I therefore see multiple intersecting target audiences for this book. The two primary ones include scientists wanting to: (1) do **Broader Impacts** – that is, to write a potentially more competitive NSF proposal; and/or (2) **benefit society** through dissemination, education, and outreach programs. Most of the audience, and indeed my emphasis, relates to audiences in the United States. I also, however, have periodically been asked to review grant proposals in other countries. Although

Broader Impacts may be called by some other term in other countries, in many instances equivalent expectations exist for professionals to provide plans and activities for general societal benefit. Thus, although primarily focused on the United States, this book might also be useful to scientists in other countries. I also hope that this book might be of interest to people outside of academe who would like to understand ways in which they can connect with scientists and participate in mutually beneficial activities and programs.

Intent, Scope, and Structure

As the name implies, the topic of this book – *Broader Impacts of Science on Society* – is potentially expansive. When I think of the scope of the table of contents, it is both daunting and unrealistic, particularly for one person to try to tackle. Thus, the emphasis of this book is Broader Impacts and societal benefit based on my experiences. While the goal for this book is to be comprehensive, that is, covering most of the relevant topics, its scope is not intended to be exhaustive. Many of the chapters could easily be books in themselves. In fact, some of them, like communications – on which I am neither an expert nor an authority – are entire disciplines for which the chapter is only scratching the surface. Nevertheless, these topics are important to cover within the overall theme of this book and are therefore included here. There are inherent emphases in how I treat the various topics. As a paleontologist, evolutionary biologist, and museum scientist, I tend to focus on the natural sciences because these are closer to my knowledge base and content domain. Nevertheless, science and STEM in the twenty-first century seek to be integrative and this book is mindful of this trend.

Because this book is based on my experiences, I oftentimes write in the first person. This is not always best practice, particularly in formal scientific writing. Nevertheless, this book is intended to be my view of the subject. I also believe that stories are engaging narrative. As such, each chapter starts with a first-person anecdote. In other sections the more widely accepted third person is mostly, but not always, used, particularly for descriptive narrative and discussion of relevant background and literature.

Most of the chapters have a similar structure. They typically include: (1) a personal anecdote; (2) some background, such as from previous studies or learning research; (3) at least one representative example or case study; and (4) a discussion of relevant best practices and broader significance. Likewise, although there is a lengthy list of about 600 references cited, in most cases these are just scratching the surface.

This overall intention of this book is to help scientists understand and develop Broader Impacts activities and programs for the benefit of society. The focus is based on my experiences over the past five decades. While not intended to be a textbook, its structure, and many of the ideas and examples presented here, resulted from a graduate seminar on Broader Impacts that I have taught at the University of Florida since 2006. The number and sequence of chapters could realistically be covered in a

four-month-long academic semester, either in an organized course or perhaps during the ubiquitous research "lab" meetings.

My Background and Acknowledgments

I have benefitted greatly because of others and formative experiences that I have had. As a child, I developed an abiding interest in dinosaurs. To me there was no more interesting place than the dinosaur halls at the American Museum of Natural History in New York, located just a train ride from where we lived in the suburbs. I truly believe in the profound impact that inspirational K–12 teachers can have on young minds. My tenth-grade earth science teacher, Mr. Greenstein, at Port Chester Senior High School (New York), encouraged my interest and built my confidence in science (Chapter 10). For his class I wrote a term paper on the fossil bird *Archaeopteryx*. I enjoyed going to the Yonkers Public Library on Saturdays, where I did the research for this paper.

As an undergraduate at Cornell University, I had the opportunity to take school groups on field trips along the shores of Lake Cayuga to collect "elephant toenails," which were fascinating 375 million-year-old fossil corals. These outings with young learners turned out to be a particularly rewarding experience. One of the joys of teaching is to see students enjoying learning and thrilled by discovery. At that time, I was also mentored by two influential Cornell geology professors, John Wells and Art Bloom, who continued to build my confidence and encouraged me to consider a career as a professional scientist.

As a graduate student at Columbia University in the early 1970s I did what most graduate students were supposed to do, or at least I think I did. My major professor, Malcolm McKenna, taught me to think and work independently. He always encouraged us to do the best science that we could and to think big thoughts – "outside the box." There was no such thing as NSF's Broader Impacts then, so we were primarily focused on doing good science and getting a job upon graduation. With regard to the latter, in 1976 I was fortunate to land an instructorship in the geology department at Yale University, which was adjacent to the Peabody Museum of Natural History (also part of Yale). During that time the museum was renovating some of its exhibit halls. Given my prior research interests as a graduate student, I was invited to participate in an update of the fossil horse display. With the help of the museum design and fabrication staff, I became involved in the update. I enjoyed the creative process of designing the exhibit and preparing its interpretive materials. In hindsight, this was the beginning of my professional interest in informal science education, now also called informal STEM learning.

Since 1977 I have been a professor and faculty curator at the Florida Museum of Natural History, which is part of the University of Florida. This position has come with the expectation that we participate in the education and outreach activities of our museum. It has been both immensely rewarding and creative to work on exhibits and public programs. In the 1990s, when we were building a new education and exhibits center, I was given the opportunity to take a break from my full-time faculty duties to be involved in the administration of exhibits and public programs. From

Fig. 0.1 *Hall of Florida Fossils* at the Florida Museum of Natural History, University of Florida (Mary Warrick photo).

1996 to 2004 I was in charge of the development of this museum facility and its programs. Despite its administrative challenges, this was highly creative and rewarding. It also provided the opportunity to communicate science through exhibits, such as in the Hall of Florida Fossils, a space that still has special meaning to me (Fig. 0.1). During this time I started reviewing NSF proposals in informal science education. These were a refreshing and innovative change from the typical science research proposals that I had reviewed for decades. It also was the same time that Broader Impacts were starting to ramp up as part of the merit review criteria for NSF proposals.

I was involved in the development of this exhibition during my time as director of the Exhibits and Public Programs division. The skeleton in the foreground of Fig. 0.1 represents the Ice Age (Pleistocene) horse *Equus* surrounded by skeletons of other evidence of past life in Florida. *Equus* has special significance because of my long-standing research interest in fossil horses (e.g., MacFadden, 1992). It also exemplifies another interest of mine – the translation of research into public exhibits and how fossil horses provide evidence for evolution (MacFadden et al., 2012).

In the mid-2000s, I become more aware of NSF's Broader Impacts and started to teach a graduate seminar on this subject (MacFadden, 2009). I have taught this course for seven semesters since that time. I thank my students in these classes for their enthusiasm. Unlike some of my more senior colleagues, who are set in their ways, the next generation "gets" NSF's Broader Impacts and related activities that benefit society. I have periodically co-taught this course with my colleague David Reed, and thank him for his insight, perspective, and shared enthusiasm.

In 2009, after participating in an NSF panel, I was encouraged to apply for, and accepted, a position as a "rotating" (fixed-term) program officer at NSF in the Directorate of Education and Human Resources (EHR). This opportunity placed me in the informal science education program the Lifelong Learning Cluster. During that year (2009–2010) at NSF I managed proposals and projects mostly related to science learning in the built environment (i.e., museums, science centers, planetaria, aquaria, nature centers, and the like). At that time NSF had a collaboration with the American Association for the Advancement of Science (AAAS) to

promote science communication via workshops at meetings and universities. I represented NSF at these events by presenting talks on Broader Impacts. I am grateful for how that year at NSF broadened my professional development. I also gained an insider's view on how committed program officers are to NSF's mission and the hard work they do. As professors, we like to think that we are dedicated and work hard; I saw the same culture at NSF. I greatly enjoyed my time there; it was critical to my thinking about Broader Impacts. There are so many colleagues there to thank, including Al DeSena, my de facto mentor, fellow rotators Sue Allen and Leslie Goodyear, and Wyn Jennings, the last of whom has encouraged me since I left NSF a decade ago.

As described in Chapter 11, my recent passion has been working with K–12 STEM teachers. The catalyst for this new direction in my career is an example of serendipity in science. After returning from NSF in 2011, I was contacted by Gary Bloom, then superintendent of Santa Cruz City Schools (California). Gary has a keen interest in fossils and paleontology. He had an enjoyable experience volunteering in the paleontology laboratory at the Smithsonian Tropical Research Institute (STRI) with Carlos Jaramillo. Gary wanted his teachers to have a similar experience. At the same time I was involved in a multi-year NSF-funded project to advance understanding of the geology and paleontology along the Panama Canal during its expansion. Carlos put Gary in contact with me. Together we wrote a series of successful NSF grants for STEM teachers to engage in the collection of fossils in Panama. We did this for five years and involved 50 teachers and three dozen scientists. I found that I enjoyed working with teachers and, as a result of this, in 2015 I applied for an "alternative sabbatical" from the University of Florida. These sabbaticals were intended for proposals that were "outside of the box," something different from the traditional hiatus, where a scientist spends time in a colleague's laboratory away from their home institution. During my alternative sabbatical in 2015–2016, I was a visiting scientist in the Santa Cruz County Office of Education (SCCOE). I am grateful to the superintendent, Michael Watkins, for allowing me to do my sabbatical at SCCOE. I am also grateful to Mary Anne James and Adam Wade for mentoring me in the K–12 ecosystem, and for so many teachers who welcomed me into their classrooms. Being a visiting scientist was a particularly rewarding part of my continued professional development. I found that I really enjoy teaching third-graders about local fossils. This has led to my newfound commitment to impacting society through K–12 outreach, education, and partnerships.

I am also grateful to my graduate students, who over the past decade have shown me that the next generation has no problem with Broader Impacts and related activities of societal benefit. To them it simply makes sense, and they are predisposed to the importance of these activities with little, if any, prodding. Students are an inspiration to me and should also be to some colleagues of my generation who still disparage these activities as taking away from their research. Much of what I have experienced over the past 40 years could not have been possible without the continued support of my home institution, the Florida Museum of Natural History at the University of Florida. I am likewise grateful for the support that I have received from grants, primarily from NSF.

While writing this book I benefitted greatly from discussions I had with colleagues and friends, most notably Douglas Jones and David Evans, both of the University of Florida. I also thank Jeff Gage and Leigh Anne McConnaughey of our photography department, who helped to organize and find photos. With much patience, Tammy Fluech cheerfully prepared most of the graphic illustrations. Many kind people, too numerous to mention here, responded to requests for images, permissions, and other information. My graduate students have remained interested and supportive, particularly during our lab meeting conversations. I thank Matt Lloyd, editor at Cambridge University Press for his insight, guidance, and patience. Zoë Pruce, also at Cambridge University Press, provided much helpful input during preparation and production of the manuscript. David Evans peer-reviewed the entire manuscript. David Jennings and Shari Ellis critically read, respectively, Chapters 17 (Project Management) and 18 (Evaluation). My student Jeanette Pirlo carefully edited early drafts of all the chapters and then did the final check of references. She showed me that even though I have written lots during my career, I have a different interpretation of the use of commas and oftentimes write in compound, run-on sentences.

The most important influence in this journey has been my lovely wife, Jeannette, who has encouraged me over the past quarter-century. She has validated that my interest in Broader Impacts and related activities is a worthy way for a scientist to contribute to society. Jeannette has been entirely supportive of me while I wrote this book, which has consumed many early mornings and evenings at home and during "workations."

In closing, I want to acknowledge the many other persons who have influenced me. I hope that although they are not mentioned by name above, they will accept my gratitude as having been influential in my professional development. I would not be where I am today professionally without them.

Abbreviations, Definitions, and Acronyms

AAAS	American Association for the Advancement of Science
ABR	accomplishment-based renewals, NSF
ADA	Americans with Disabilities Act
ADBC	Advancing Digitization of Biodiversity Collections, NSF
AISL	Advancing Informal STEM Learning, NSF
AMNH	American Museum of Natural History
AP	advanced placement
AR	augmented reality
ARRA	American Recovery and Reinvestment Act
ASTC	Association of Science and Technology Centers
ATE	Advanced Technological Education, NSF
BIO	Directorate for Biological Sciences, NSF
BOP	Billion Oyster Project
BP	Broadening Participation, NSF
CAISE	Center for Advancement of Informal Science Education
CCEP	Climate Change Education Partnership, NSF
CoP	community of practice
CRPA	Communicating Research to Public Audiences, NSF
DCL	Dear Colleague Letter, NSF
DEI	diversity, equity, and inclusion
DGE	Division of Graduate Education, NSF
DORA	Declaration on Research Assessment
DRL	Division of Research on Learning, NSF
DUE	Division of Undergraduate Education, NSF
EHR	Directorate for Education and Human Resources, NSF
ELL	English language learners
EPSCoR	Experimental Program to Stimulate Competitive Research, NSF
ESL	English as a second language
FCAT	Florida Comprehensive Assessment Test
FHC	Fossil Horses in Cyberspace
FLMNH	Florida Museum of Natural History, UF
GABI	Great American Biotic Interchange
GBIF	Global Biodiversity Information Facility
GEO	Directorate for Geosciences, NSF
GRFP	Graduate Research Fellowship Program (also GRF), NSF
HRD	Division of Human Resource Development, NSF
iDigBio	Integrated Digitized Biocollections

IGY	International Geophysical Year
IMLS	Institute of Museum and Library Services
INCLUDES	Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science, NSF
IRB	Institutional Review Board
ISE	Informal Science Education
ISL	Informal STEM learning
ITEST	Innovative Technology Experiences for Students and Teachers, NSF
JIF	journal impact factor
K–12	Schools in the United States (Kindergarten through grade 12), and encompassing elementary, middle, and high school
K–16	K–12 plus four years of undergraduate college or university education
MSP	Math and Science Partnerships, NSF
MACOS	"Man: A Course of Study"
NAS	National Academy of Sciences; also National Academies of Sciences, Engineering, and Medicine
NGSS	Next Generation Science Standards
NIH	National Institutes of Health
NOS	nature of science
NPS	National Park Service
NRT	NSF Research Traineeship
NSB	National Science Board
NSDL	National Science Digital Library
NSF	National Science Foundation, United States
NSTA	National Science Teaching Association
OA	open access
OIA	Office of Integrative Activities, NSF
OISE	Office of International Science and Engineering, NSF
PD	professional development, mostly in relation to K–12 teachers
PI	principal investigator
PIRE	Partnerships for International Research and Education, NSF
PPSR	public participation in scientific research
R&D	research and development
R&RA	Research and Related Activities, NSF
RANN	Research Applied to National Needs
RCN	Research Coordination Network, NSF
RET	Research Experiences for Teachers, NSF
REU	Research Experiences for Undergraduates, NSF
ROI	return on investment
SBE	Directorate for Social, Behavioral and Economic Sciences, NSF
SBIR	Small Business Innovation Research, NSF
SCCOE	Santa Cruz County Office of Education, California
SEES	Science, Engineering, and Education for Sustainability, NSF

SGER	Small Grants for Exploratory Research, NSF
SMP	Science Masters Program, NSF
STC	Science and Technology Centers, NSF
STEAM	STEM plus art
STEM	science, technology, engineering, and mathematics
STRI	Smithsonian Tropical Research Institute, Panama
TACC	Texas Advanced Computing Center, University of Texas
TCN	Thematic Collections Network, NSF
TED	Technology, Entertainment, Design
UF	University of Florida
VR	virtual reality
VSA	Visitor Studies Association