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# Transdisciplinary Science

## A Path to Understanding the Interactions Among Ocean Acidification, Ecosystems, and Society

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Merging science and society is the foundation for transdisciplinary science; symbolized here as a handshake between scientist and fisherman as the science community, resource managers, industry, policymakers and coastal communities work together to achieve solution-oriented results for addressing environmental impacts and societal issues resulting from ocean acidification. *Image concept and design: Kimberly K. Yates, photo credit: Karen Morgan and Lisa Robbins, graphic art: Betsy Boynton*

“ We discuss the challenges associated with integrating ocean acidification science across funding agencies, institutions, disciplines, topical areas, and regions, and the value of unifying science objectives and activities to deliver insights into local, regional, and global scale impacts. ”

**ABSTRACT.** The global nature of ocean acidification (OA) transcends habitats, ecosystems, regions, and science disciplines. The scientific community recognizes that the biggest challenge in improving understanding of how changing OA conditions affect ecosystems, and associated consequences for human society, requires integration of experimental, observational, and modeling approaches from many disciplines over a wide range of temporal and spatial scales. Such transdisciplinary science is the next step in providing relevant, meaningful results and optimal guidance to policymakers and coastal managers. We discuss the challenges associated with integrating ocean acidification science across funding agencies, institutions, disciplines, topical areas, and regions, and the value of unifying science objectives and activities to deliver insights into local, regional, and global scale impacts. We identify guiding principles and strategies for developing transdisciplinary research in the ocean acidification science community.

## INTRODUCTION

Ocean acidification (OA), defined as the absorption of CO<sub>2</sub> by the ocean and the resultant decrease in pH and other changes in seawater chemistry, is a growing threat to marine organisms and ecosystems and the services they provide (Doney et al., 2009; Gattuso et al., 2014; Hoegh-Guldberg et al., 2014; Pörtner et al., 2014). In the last decade, researchers working independently, in groups within a particular discipline, and in large projects and programs that encourage multidisciplinary work have significantly advanced our understanding of the potential impacts of OA. An accumulating body of literature illuminates the complexity of OA as a driver of environmental change, its role in contributing to multi-stressor impacts, and the potential importance of its socioeconomic consequences.

OA involves chemical, physical, and

biological processes. Therefore, OA science has naturally evolved to include both the multidisciplinary and the interdisciplinary approaches that have traditionally been applied in the ocean sciences (Stokols et al., 2003; Box 1). These approaches have greatly advanced our basic knowledge of OA on a short-term, species-specific basis. However, there is only limited scientific progress in predicting long-term impacts at the ecosystem level, understanding societal implications, and developing societal adaptation to consequences of OA—and even more limited political progress in addressing its causes. Thus, the OA research community has generally been unable to answer the main questions of resource managers and policymakers: Just how serious is the threat of ocean acidification? And, what should we be doing about it?

Faced with similar limitations in

understanding long-term threats from the growing imbalance between human activities and the environment in mountain ecosystems, the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the Swiss Man and Biosphere Programme developed a transdisciplinary (TD) science approach (Box 1) in 1979 to facilitate development of research, adaptation, and mitigation strategies (Messerli and Messerli, 2008). This approach has also been applied in the international health research community, where it has revolutionized the study of “real-world” global health issues as affected by social, economic, political, and institutional factors (Rosenfield, 1992). Recent efforts to incorporate TD research into the ocean sciences have proven successful for examining issues of ecosystem health, climate change, and land-sea interactions (e.g., Center for Ocean Solutions; <http://www.centerforoceansolutions.org>). We propose a TD research approach for OA to fully integrate strategic scientific effort, directed at the interactions among OA, ecosystems, and society. We discuss the current state of collaboration, partnership, and disciplinary linkages for OA science; identify organizational, management, and science process impediments; and make recommendations for developing a TD approach for future OA projects and programs to address both scientific and societal needs.

## BOX 1. TRANSDISCIPLINARY RESEARCH

Merging natural and social science perspectives and practices to produce solutions for societally relevant problems is the core of transdisciplinary (TD) science. A comprehensive guide for developing TD research provides a broad conception of requirements and goals of a TD research process from a synthesis of the literature (Pohl and Hadorn, 2007):

*There is a need for TD research when knowledge about a societally relevant problem field is uncertain, when the concrete nature of problems is disputed, and when there is a great deal at stake for those concerned by problems and involved in dealing with them. TD research deals with problem fields in such a way that it can: a) grasp the complexity of problems, b) take into account the diversity of life-world and scientific perceptions of problems, c) link abstract and case specific knowledge, and d) constitute knowledge and practices that promote what is perceived to be the common good.*

We base our discussion on the following definitions of methods for integrating the science disciplines.

- *Multidisciplinary* researchers in different disciplines work independently or sequentially, from their own disciplinary perspectives, to address a common goal or problem (Stokols et al., 2003).
- *Interdisciplinary* researchers work jointly from their own disciplinary perspectives to integrate knowledge and address a common goal or problem (Stokols et al., 2003).
- *Transdisciplinary* researchers work jointly to grasp the complexity of problems from diverse scientific and societal perspectives, integrate natural and social science disciplines, alter discipline-specific approaches, and focus on problem solving for what is perceived to be the common good (Rosenfield, 1992; Pohl and Hadorn, 2007).

The need for TD research stems from a history of excluding the human component from founding principles of science. The evolution of science toward transdisciplinarity is detailed in Hadorn et al. (2008) and summarized here. Modern science practice was shaped by Aristotle's concept (384–322 BCE) that "scientific knowledge is universal, explanatory, and demonstrated to be true by standard, teachable, and learnable methods; and, therefore, must be detached from the life-world that reflects choices and opinions based on value." These principles resulted in dissociation of natural science from philosophy and development of specialized disciplines in the sciences that are fundamental to global science practice today. During the seventeenth and eighteenth centuries, science and technological innovation improved human standards of living and increased quantities of goods available, but led to criticism of founding principles that separated empirical science from real-world issues. Early paradigms (mid-eighteenth century) for "systems science" examined complex systems as sets of interrelated elements (science, cultures, values). Development of "systems theory" in the 1940s led to recognition that progressive fragmentation of the sciences into specialized disciplines becomes a major risk for society because it prevents recognition of possible negative side effects. Appreciating this risk, Jantsch (1972) proposed the term and concepts for transdisciplinarity as an integrative approach for coordinating disciplines in government, industry, and academia to work toward a common purpose that plans for society as a whole. Discussion of pioneering TD studies and experiences are available in Hadorn et al. (2008).

## THE STATE OF COLLABORATION, PARTNERSHIP, AND INTEGRATION

When OA emerged as an issue of concern in the early 2000s (Royal Society, 2005), it soon became clear that much more research was needed to determine both its scientific importance and wider implications. Directed funding calls and coordinated programs provided the main mechanisms for accelerating such effort, with the latter being particularly effective in stimulating collaborations between research groups with complementary interests and facilitating knowledge exchange between researchers and research users in both public and private sectors.

Many multidisciplinary national and international OA programs and projects have already been established or completed (Table 1). The European Union (EU) pioneered coordinated OA research with support for the European Project on Ocean Acidification (EPOCA) from 2008, and subsequently the Mediterranean Sea Acidification in a Changing Climate (MedSeA) project from 2011. Two nationally funded OA activities in Europe closely followed: the German Biological Impacts of Ocean Acidification program (BIOACID) in 2009, and the UK Ocean Acidification research program (UKOA) in 2010. In the United States, Congress passed the Federal Ocean Acidification Research and Monitoring Act (FOARAM, 2009). This legislation resulted in the creation of the Interagency Working Group on Ocean Acidification (IWGOA) in 2009, the National Oceanic and Atmospheric Administration (NOAA) Ocean Acidification Program in 2011, and the first federal OA strategic plan (IWGOA) in 2014. It also provided guidance for US National Science Foundation (NSF) directed calls on OA starting in 2010. Laffoley and Baxter (2012) summarize other recent and ongoing OA programs, and major initiatives are listed in Table 1.

The ability of the global OA research

community to work across national boundaries has been demonstrated by many international outputs relating to policy outreach (e.g., Royal Society, 2005; IPCC, 2007; Monaco Declaration, 2008; Interacademy Panel, 2009; Turley et al., 2012; publications by the Ocean Acidification International Reference User Group). The community has also created a range of international working groups and coordination initiatives, including the SOLAS-IMBER (Surface Ocean-Lower Atmosphere Study-Integrated Marine Biogeochemistry and Ecosystem Research) Working Group on Ocean Acidification, the Ocean Acidification International Coordination Centre, and the Global Ocean Acidification Observing Network.

Despite these accomplishments, recent reviews of the state of OA science

(Pfister et al., 2014; many papers in this issue) identify significant deficiencies in the ability of OA researchers to produce solution-oriented knowledge. In particular, there are gaps regarding the characterization of OA in environmental systems (Andersson et al., 2015; Martz et al., 2015; Salisbury et al., 2015; Sutton et al., 2015, all in this issue), the linkage of measurements to processes (Breitburg et al., 2015; Busch et al., 2015; Levin et al., 2015; McLaughlin et al., 2015, all in this issue), and the development of predictive capabilities (Busch et al., 2015, in this issue). Together, these gaps impede the transfer of knowledge across thematic elements, jeopardizing the achievement of realistic projections of environmental and societal impacts of OA. While OA is becoming part of the wider climate change debate, it is not yet mainstream,

and public awareness of OA still remains low (Cooley et al., 2015, in this issue).

A TD approach to OA research would address, by design, the full range of such issues, from molecular processes to societal responses. Lang et al. (2012) present a framework for TD science that includes three phases: (1) collaboratively framing the problem and building a research team to create an integrated pathway for scientific innovation and problem solving, (2) co-producing solution-oriented and transferable knowledge through collaborative research, and (3) re-integration and application of the produced knowledge in both scientific and societal practice (Figure 1). Synthesis of knowledge is incorporated throughout the process (rather than as a last step), resulting in more efficient and rapid development of applied results and products. While TD

**TABLE 1.** Major sub-national, national, and international (regional and global) ocean acidification programs and initiatives.

PROGRAM/INITIATIVE	ACRONYM	WEB LINK
<b>SUB-NATIONAL</b>		
California Current Acidification Network	C-CAN	<a href="http://c-can.msi.ucsb.edu">http://c-can.msi.ucsb.edu</a>
Northeast Coastal Acidification Network	NECAN	<a href="http://www.neracoos.org/necan">http://www.neracoos.org/necan</a>
Southeast Ocean and Coastal Acidification Network	SOCAN	<a href="http://secoora.org/SOCAN">http://secoora.org/SOCAN</a>
<b>NATIONAL</b>		
Biological Impacts of Ocean Acidification (Germany)	BIOACID	<a href="http://www.bioacid.de">http://www.bioacid.de</a>
Chinese Ocean Acidification Initiative	CHOICE-C	<a href="http://973oceanarbon.xmu.edu.cn/index.asp">http://973oceanarbon.xmu.edu.cn/index.asp</a>
NOAA Ocean Acidification Program	NOAA OAP	<a href="http://oceanacidification.noaa.gov">http://oceanacidification.noaa.gov</a>
UK Ocean Acidification research programme	UKOA	<a href="http://www.oceanacidification.org.uk">http://www.oceanacidification.org.uk</a>
US Interagency Working Group on Ocean Acidification	IWGOA	<a href="http://oceanacidification.noaa.gov/IWGOA.aspx">http://oceanacidification.noaa.gov/IWGOA.aspx</a>
US Ocean Carbon and Biogeochemistry Ocean Acidification Subcommittee	OCB-OA	<a href="http://www.whoi.edu/OCB-OA/page.do?pid=32496">http://www.whoi.edu/OCB-OA/page.do?pid=32496</a>
<b>INTERNATIONAL (REGIONAL)</b>		
European Project on Ocean Acidification	EPOCA	<a href="http://www.epoca-project.eu">http://www.epoca-project.eu</a>
Mediterranean Sea Acidification in a Changing Climate	MedSeA	<a href="http://medsea-project.eu">http://medsea-project.eu</a>
<b>INTERNATIONAL (GLOBAL)</b>		
Global Ocean Acidification Observing Network	GOA-ON	<a href="http://www.goa-on.org">http://www.goa-on.org</a>
Ocean Acidification and The Economic Impact on Fisheries and Coastal Society	None	<a href="http://www.iaea.org/nael/page.php?page=2259">http://www.iaea.org/nael/page.php?page=2259</a>
Ocean Acidification International Coordination Centre	OA-ICC	<a href="http://www.iaea.org/ocean-acidification/page.php?page=2181">http://www.iaea.org/ocean-acidification/page.php?page=2181</a>
Ocean Acidification international Reference Users Group	OAIrUG	<a href="http://www.iaea.org/ocean-acidification/page.php?page=2198">http://www.iaea.org/ocean-acidification/page.php?page=2198</a>
Ocean Acidification Working Group of the Surface Ocean-Lower Atmosphere Study and Integrated Marine Biogeochemistry and Ecosystem Research Project	SOLAS-IMBER (SIOA-WG)	<a href="http://www.imber.info/index.php/Science/Working-Groups/SOLAS-IMBER-Carbon">http://www.imber.info/index.php/Science/Working-Groups/SOLAS-IMBER-Carbon</a>

science seems easily prescribed as a path forward for the strategic advancement of OA science, is the OA community ready to meet its challenges?

## KEY ELEMENTS AND CHALLENGES

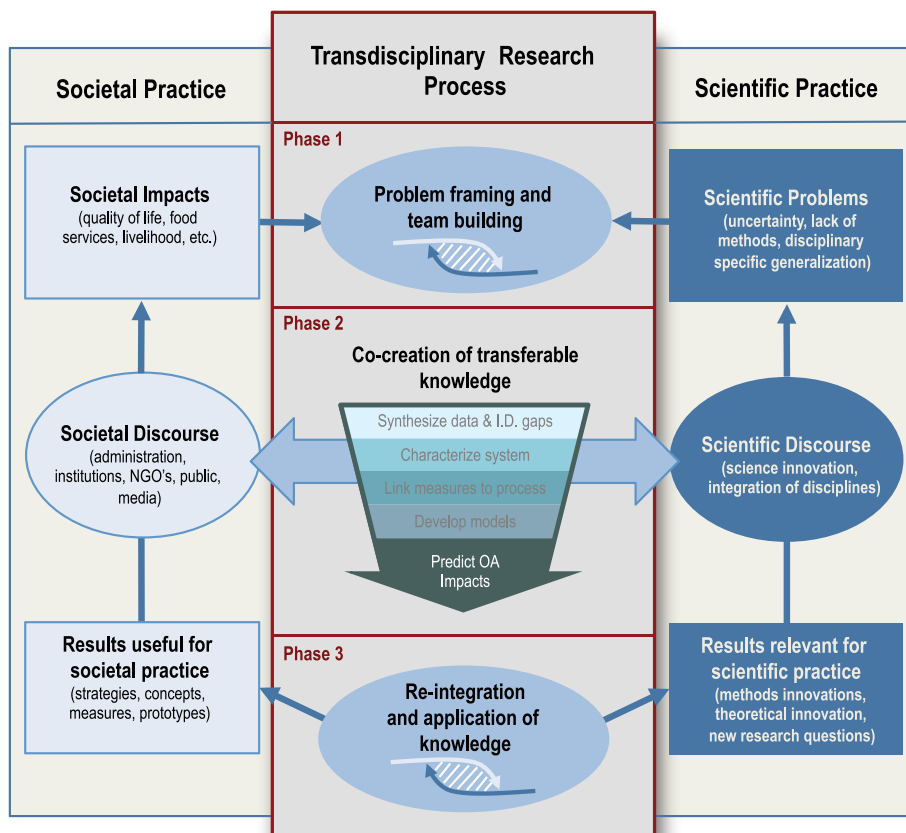
During the 2013 national meeting of US OA scientists and resource managers (Mathis et al., 2015a), we examined key elements of existing multidisciplinary studies, programs, and strategies to identify the current challenges and impediments to OA science, and the readiness of the OA community to pursue a TD approach. These elements included: science, policy, partners, funding agencies, other stakeholders, project management, synthesis of results, application to resource management, cultural mindset, communication structure, outreach and community involvement, and social science/policy elements. OA efforts examined included projects currently

funded by the US NSF, programs of participating agencies of the IWGOA, and non-US national and international OA research activities. We identified key challenges and impediments to OA science, recommended solutions (Table 2), and discussed common challenges faced in TD research (Lang et al., 2012). Challenges were grouped into four themes: (1) science coordination, (2) capacity building, (3) stakeholder outreach, and (4) communications. These challenge themes are well aligned with the main tasks of the Ocean Acidification International Coordination Centre, indicating that the global OA community recognizes the need for support in these areas, and appears to be well prepared to transition to a TD science approach.

A critical element for the TD approach is the identification of common goals that span the disciplines and are embraced by all participating individuals and institutions. Such unifying

goals, associated questions, and hypotheses have been clearly formulated by the OA community (e.g., IGWOA, 2014; <http://www.iaea.org/ocean-acidification/page.php?page=2181>). Moving beyond recognition of these goals to achieving them requires not only a cultural mindset that values integration but also compromise and flexibility of agency missions and funding mechanisms, as well as adaptive planning and management to achieve consensus among collaborative entities. We conducted a survey of leaders or major participants in national and international multidisciplinary OA and other environmental programs (Table 3) and found them well poised to transition to a TD approach. The respondents reported few issues with integrating scientists from the physical and biological disciplines, likely reflecting original program design and the relatively long history of multidisciplinary research in the ocean sciences. However, integration of social scientists and economists created more difficulty (Table 4). The need to merge natural and social sciences to produce transformative results is a key driver of, and the foundation for, a movement toward the TD scientific process.

Despite these challenges, elements of previous and ongoing national and international programs could serve as good models for a US OA program based on a TD approach (Table 1). High-level mandates (e.g., FOARAM, 2009; IWGOA, 2014) emphasize an integrative approach based on multi-agency, interdisciplinary research. Grass roots efforts to integrate multidisciplinary research demonstrate the value of this approach (e.g., Newton, 2007; McLaughlin et al., 2013; and Barton et al., 2015; Gledhill et al., 2015; Mathis et al., 2015b; Phillips et al., 2015, all in this issue), and priority goals have converged on a global basis. OA researchers from around the world independently reached similar conclusions regarding current impediments (Table 2) to advancing OA science and identified solutions that would help develop a TD approach. The US IWGOA identified several



**FIGURE 1.** Summary of the transdisciplinary research process, modified for ocean acidification science. Arrows indicate flow of knowledge. *Adapted from Lang et al. (2012)*

**TABLE 2.** Common challenges in transdisciplinary science (from Lang et al., 2012), challenges, and solutions identified by the ocean acidification science community.

TRANSDISCIPLINARY SCIENCE CHALLENGES	OA SCIENCE COMMUNITY CHALLENGES	SOLUTIONS
<b>SCIENCE COORDINATION</b>		
Unbalanced problem ownerships	<ul style="list-style-type: none"> <li>• Diverging agency missions</li> <li>• Embracing common goals</li> <li>• Committing adequate funding</li> </ul>	<ul style="list-style-type: none"> <li>• Instill and reward appropriate cultural mindset through added value to promote collaborations</li> <li>• Embrace compromise and flexibility to achieve consensus among participants</li> <li>• Establish metrics for implementation of TD science</li> </ul>
Conflicting methodological standards	<ul style="list-style-type: none"> <li>• Unison in vocabulary used for clear, unbiased data interpretations</li> <li>• Standardizing methods</li> </ul>	<ul style="list-style-type: none"> <li>• Use best practices guides</li> <li>• Adopt standardized data labeling and reporting methods</li> </ul>
Lack of integration across knowledge types, organizational structures, communicative styles, or technical aspects	<ul style="list-style-type: none"> <li>• Disparities in data, time, spatial resolution</li> <li>• Uncertainties (Busch et al., 2015, in this issue)</li> <li>• Linking observations to processes and predictions</li> <li>• Difference in timing of agency planning activities, reporting requirements, info dissemination practices</li> </ul>	<ul style="list-style-type: none"> <li>• Define outcome from start and plan in detail</li> <li>• Implement outcome oriented project structure</li> <li>• Select appropriate leaders to facilitate integration</li> <li>• Define and implement metrics to integrate agency support</li> </ul>
Discontinuous participation	<ul style="list-style-type: none"> <li>• Funding schedules and limitations</li> <li>• Changing agency missions</li> </ul>	<ul style="list-style-type: none"> <li>• Perform realistic assessment of funding sources and mission requirements of funding entities</li> <li>• Creative approaches for transferring funding and identifying links for OA to other funding programs (e.g., multi-stressors, climate adaptation) to open funding opportunities</li> <li>• Agencies commit to partnership and add to mission statements</li> </ul>
Tracking scientific and societal impacts	<ul style="list-style-type: none"> <li>• Establishing measures of success</li> </ul>	<ul style="list-style-type: none"> <li>• Implement science progress and process implementation metrics</li> </ul>
<b>CAPACITY BUILDING</b>		
Fear of failure	<ul style="list-style-type: none"> <li>• Data sharing and synthesis</li> <li>• Achieving project legacy</li> <li>• Dependency of long-term multi-source funding sources</li> </ul>	<ul style="list-style-type: none"> <li>• Establish requirements for data reporting.</li> <li>• Identify and plan for the desired outcome/product that results from achieving the common goal.</li> <li>• Build realistic objectives that are achievable steps with respect to funding limitations</li> <li>• Build on grass-roots efforts using existing resources</li> </ul>
Limited, case-specific solution options	<ul style="list-style-type: none"> <li>• Transfer of knowledge and lessons learned across ecosystems and geographic regions</li> </ul>	<ul style="list-style-type: none"> <li>• Identify the methods and processes that can be transferred across boundaries and the limitations of information that does not apply across boundaries—be specific in reporting</li> <li>• Fund international collaboration for knowledge transfer</li> </ul>
<b>STAKEHOLDER OUTREACH</b>		
Lack of problem awareness or insufficient problem framing	<ul style="list-style-type: none"> <li>• Outreach to and support from public</li> <li>• Communication of needs to policymakers, funders, and stakeholders</li> <li>• Clearly articulating goals and realistic objectives</li> </ul>	<ul style="list-style-type: none"> <li>• Funding for knowledge exchange to policymakers</li> <li>• Involve communications experts (e.g., COMPASS) to assist with broad scale communications</li> </ul>
Insufficient legitimacy of the team or actors involved	<ul style="list-style-type: none"> <li>• Identifying, informing, and engaging stakeholders</li> <li>• Involving stakeholders in planning process</li> <li>• Processes for keeping stakeholders involved</li> </ul>	<ul style="list-style-type: none"> <li>• Ensure collaboration at all program and project levels and stages—planning, research, interpretation, and product development</li> <li>• Involve stakeholders through technical and citizens advisory groups</li> </ul>
Lack of legitimacy of transdisciplinary outcomes	<ul style="list-style-type: none"> <li>• Generating actionable knowledge</li> <li>• End-user/stakeholder value</li> </ul>	<ul style="list-style-type: none"> <li>• Define and develop specific usable products in cooperation with stakeholders</li> </ul>
<b>COMMUNICATION</b>		
Vagueness and ambiguity of results	<ul style="list-style-type: none"> <li>• Transparency, repetition, consistency, clarity in relaying plans and message to all levels</li> </ul>	<ul style="list-style-type: none"> <li>• Include senior scientists as representatives for communication to programs, policymakers, and participating scientists</li> <li>• Choose leaders with appropriate communication skills</li> </ul>
Capitalizing on distorted research results	<ul style="list-style-type: none"> <li>• Misrepresentation of data</li> </ul>	<ul style="list-style-type: none"> <li>• Improve outreach and education to the public and stakeholders through involvement in citizen and technical advisory boards</li> </ul>

challenges to meeting national goals for OA (IWGOA, 2014) by recognizing that: (1) US agencies need to focus on goals related to their individual missions that are not necessarily fully complementary; (2) it is difficult to prescribe goal-related work because OA research is primarily funded through competitive processes based on merit, not topic; (3) the rapid development of OA science makes it difficult to compare quantitative metrics of OA research success with those of other fields; and (4) societally relevant goals for OA (such as developing adaptation and mitigation strategies and vulnerability assessments) are not necessarily prioritized in federal agency plans. Solutions to these challenges require improved integration of agency efforts to reach long-term goals, and include: (1) facilitating interagency coordination to address gaps, share results, and deliver outcomes that cannot be achieved by agencies working alone; (2) producing metrics of success based on tracking federal activity and collaborative progress toward goals;

and (3) retaining flexibility to revise strategic research plans as new research and monitoring gaps are identified. While these issues may seem generic, particular problems in applying the TD approach to OA relate to the diversity of organizational structures involved and the timing of funding agency programs and their strategic planning processes—that is, aligning agency missions and objectives (which often differ) to work toward a common goal and organizing and integrating diverse funding sources. These difficult challenges require creative solutions that may need several years to fully resolve for OA research.

### APPLIED PLANNING AND ORGANIZATION

Planning, organizing, and managing a TD science strategy requires strong leadership, an outcome-driven structure, and effective communication pathways from the outset. The ideal conceptual model of TD research considers such activities as “interface practice”:

connecting societally driven needs, such as those of policymakers, with the expertise of scientists, and facilitating communication, knowledge exchange, and effective learning by all those involved (Jahn, 2008; Lang et al., 2012).

### Focusing on the Science

The organization and management structure of TD OA projects and programs should be designed to fully support outcome-oriented science. Otherwise, there is risk that the needs of scientists are only partially met, goals become fragmented, and results do not fully support stakeholder and community needs. Although the exact prescription of disciplinary OA science to address program-wide, integrated objectives will need to be project-, region-, or ecosystem-specific, the internationally recognized priority OA science goals (from the programs and activities in Table 1) provide common themes and driving forces within a framework that spans the full range of OA science.

TABLE 3. Overview of major multidisciplinary research programs.

		BIOACID National	UKOA National	EPOCA International	MEDSEA International	NEP National
Funding (million US \$)	Total	\$23M	\$20M	\$8.2M	\$8.2M	–
	Per year	\$3.8M	\$4M	\$2M	\$2.8M	\$0.5 per site; \$15.4 all sites
Duration (start and end dates)		2009–2015 (renewal proposed)	2010–2015	2008–2012	2011–2014	1987– present
Number of projects or sub-projects within program		~45	7	16	7	25–100
Numbers of disciplines covered in program		10	10	5	4	6–10
Number of participating institutions		14	26	32	22	10–20
Number of participating researchers		~50	~120	~160	~100	Varies
Publication record	Total	≥180	~210	~200	≥80	–
	Peer reviewed	≥130	~180	~200	≥80	–
Average impact factor		3.4	–	–	3.9	–
Published review of program available		No	No	No	No	Yes
Number of direct end user groups		7	~50–100 via Ocean Acidification international Reference User Group (OAIRUG)	~30–50 via EPOCA Reference User Group	~20 Mediterranean Reference User Group (MRUG)	5–10 for each NEP



Figure 2 mechanistically illustrates an idealized OA program, showing the intended integration of science elements that work together (as gears that drive each other in an engine) toward the ultimate goal of projecting future impacts to ecosystems and society. In a TD scenario, the work is outcome-oriented, with objectives formulated to produce results that achieve transformative outcomes affecting societal and scientific practice. The outcomes reflect the driving forces (relating to stakeholder needs), and are only reached through participation and

support from every team member and stakeholder throughout the process. This structure also illustrates the potential risk for fragmentation of objectives and goals. Multidisciplinary studies may be able to achieve results through a similar structure; however, they can encounter difficulties in reintegrating those results due to the broad range of challenges identified in Table 2. TD science can be impeded if even one element (gear, Figure 2) fails to fully achieve its objectives.

Barton et al. (2015, in this issue) provide a good example of applied planning

that reflects a TD OA approach and resulted in the solution to, and mitigation strategies for, an immediate economic and societal problem within the US Pacific Northwest shellfishery community. Recognizing severe declines in commercial production of shellfish larvae in 2007, hatchery managers partnered with multidisciplinary teams of scientists to collaboratively identify the cause of the problem as coastal acidification by conducting targeted research and monitoring that linked ocean chemistry and physical oceanography with biological (shellfish)

**TABLE 4.** Perspectives on multidisciplinary science and recommendations for future ocean acidification programs. Programs listed in Table 3 were asked how they could have been more effective as multidisciplinary programs and how a new program could address such issues. Responses are summarized below.

PROGRAM	ISSUE	SOLUTION
BIOACID	Provide a more integrated assessment of OA impacts and consequences	Involve social scientists, especially economists, early on in the project
	Be more societally relevant	Involve stakeholders from the beginning
	Have stronger community outreach	Involve PR experts in the program
UKOA	Relatively short lifetime of program, single funding opportunity for main awards caused limited scope for iterative interactions between components (e.g., between modeling and fieldwork; experimental studies and socioeconomics) and inefficient use of skills/training of newly created OA research community	Recognize that OA is a long-term, strategic problem, requiring sustained support by funders and at least two funding rounds to allow for program evolution
	Tendency for main effort of component consortia to be directed at consortium goals rather than those of the program as whole	Use incentives to develop new collaborations between research groups, not just linkages that were identified in original proposals
EPOCA	Addressing socioeconomic issues associated with OA	Include social scientists and economists in the project from the beginning
MedSeA	Difficulty fully integrating the results	Allow adequate time to compare and integrate results from different sub-projects
	Providing risk assessment and adaptation strategies to local communities	Design program to provide these products and include appropriate personnel
NEP	Keeping up with emerging issues as the project proceeds	Retain the ability to bring in new partners during the course of the project
	Having broad participation on advisory panels.	Include economists, social scientists, science communicators, and Earth scientists
<b>SPECIFIC RECOMMENDATIONS</b>		
<ul style="list-style-type: none"> <li>• International coordination is essential. Funding from national programs should assist international collaboration, be flexible, simple, and quick to take advantage of “added value” opportunities as they arise.</li> <li>• Effective coordination requires heroes/heroines as leaders to drive key issues forward, with broad support from fellow scientists, funders, and decision makers (at national, international, and intergovernmental levels).</li> <li>• The rationale for international coordination should be based on scientific need, cost effectiveness, national policy requirements, and the delivery of sustainable development.</li> <li>• Effective, coordinated summaries for policymakers are essential for bringing the latest scientific findings to key research users for societal benefit.</li> <li>• Institutional and international coordination takes time and effort. Build on existing international coordination efforts to ensure that they are appropriate vehicles for a rapidly changing future.</li> <li>• Include social scientists and economists early in program development to ease integration by training participants in both natural and social sciences to bridge the fields.</li> <li>• Make sure that stakeholder needs are met, and have adequate outreach to the general public.</li> <li>• Advisory boards should include executive boards of funders and policy boards (that meet annually) to ensure continuity of support and relevancy of activities to agency missions.</li> <li>• Large project or program coordinators will necessitate full time management. Coordinators should have appropriate science background, but should not perform science activities.</li> </ul>		

response. An integrated team of science and industry experts applied those results toward developing and implementing new technology for locally mitigating the problem. They worked with policymakers to apply that knowledge for development of a Pacific Coast Shellfish Growers Association monitoring network that has fundamentally changed

commercial hatchery practices in the region and community views on the importance of changing seawater chemistry to community economics. This partnership between a diverse group of scientists, industry representatives, resource managers, and tribal groups put a new perspective on the complexities and challenges of acidification in the coastal

zone as compared to the open ocean and resulted in the development of the California Current Acidification Network to facilitate community monitoring, transfer of knowledge, and reintegration of results to understand societal and economic impacts of OA in the coastal zone. Cooley and Doney (2009) estimated the long-term economic impacts of OA to the US shellfish industry, but point out that economic and social sciences are needed to understand how markets, prices, and communities will respond to declining fish harvests and how to mitigate socio-economic impacts.



**FIGURE 2.** The core of the transdisciplinary research process is integrating science by connecting component activities. An idealized transdisciplinary ocean acidification (OA) science strategy integrates multidisciplinary science tasks to work toward common, outcome-oriented objectives and goals in response to driving forces that reflect stakeholder needs. *Graphics by Betsy Boynton, USGS*

### Building a Good Team with Strong Leadership

The leadership of TD OA science requires strong cognitive, structural, and processual skills (Gray, 2008). Cognitive tasks focus on communicating group goals and methods for achieving them while promoting individual creativity. Structural leadership tasks focus on discipline coordination and information exchange among the team and the stakeholders. Processual tasks include designing meetings, setting process ground rules, identifying tasks to support project objectives, promoting effective communication, and mediating disagreements that often arise when participants move beyond their disciplinary comfort zones. These processes promote successful implementation of TD science through whole-team understanding of the diversity of scientific and social perspectives (for both specific problems and overall goals) in order to develop “common good” solutions (Pohl and Hadorn, 2007).

Advisory boards for TD OA programs are expected to include decision makers and stakeholders that represent driving forces and interests in outcomes. Science elements (gears in Figure 2) are likely to be facilitated and managed by task leaders who coordinate the activities of a consortium, work package, or task level to provide guidance to researchers, report progress, and synthesize results at relevant subprogram levels.

Multiple leaders should work collaboratively to develop and maintain a stable network of participants by transferring knowledge to promote innovation and solve problems, developing consensus on implementable actions, and liaising between science teams and stakeholders (Figure 3). Developing and maintaining diverse, dedicated, and active steering committees provide guidance, support, and continuity for multiple leaders who may come and go throughout the development and life of projects or programs. US regional OA monitoring networks (Barton et al., 2015; Gledhill et al., 2015, both in this issue; <http://secoora.org/SOCAN>) have adopted this approach by including local, state, and national representatives from science, resource management, community interests, and industries on founding steering committees and advisory boards. These programs also benefit from knowledge transfer across regions by linkage with the US Integrated Ocean Observing System (<http://www.ioos.noaa.gov/welcome.html>). However, such programs could benefit from incorporating social scientists and providing student opportunities in communication, economics, human impacts, and education to begin developing long-term partnerships and participation with the social sciences.

In the United States, a key organizational challenge for the OA community is finding ways to link federal, state, and local funding sources and mission mandates with scientific and community interests. The US National Estuary Program (NEP) developed an approach for overcoming these challenges by enlisting technical advisory and citizen advisory committees. Schneider et al. (2003) found that the networks in NEP areas span more levels of government, integrate more experts into policy discussions, nurture stronger interpersonal ties among stakeholders, and create greater faith in the procedural fairness of local policy than other comparable initiatives. This model could therefore serve as an effective means for organizing regional-scale OA studies relevant

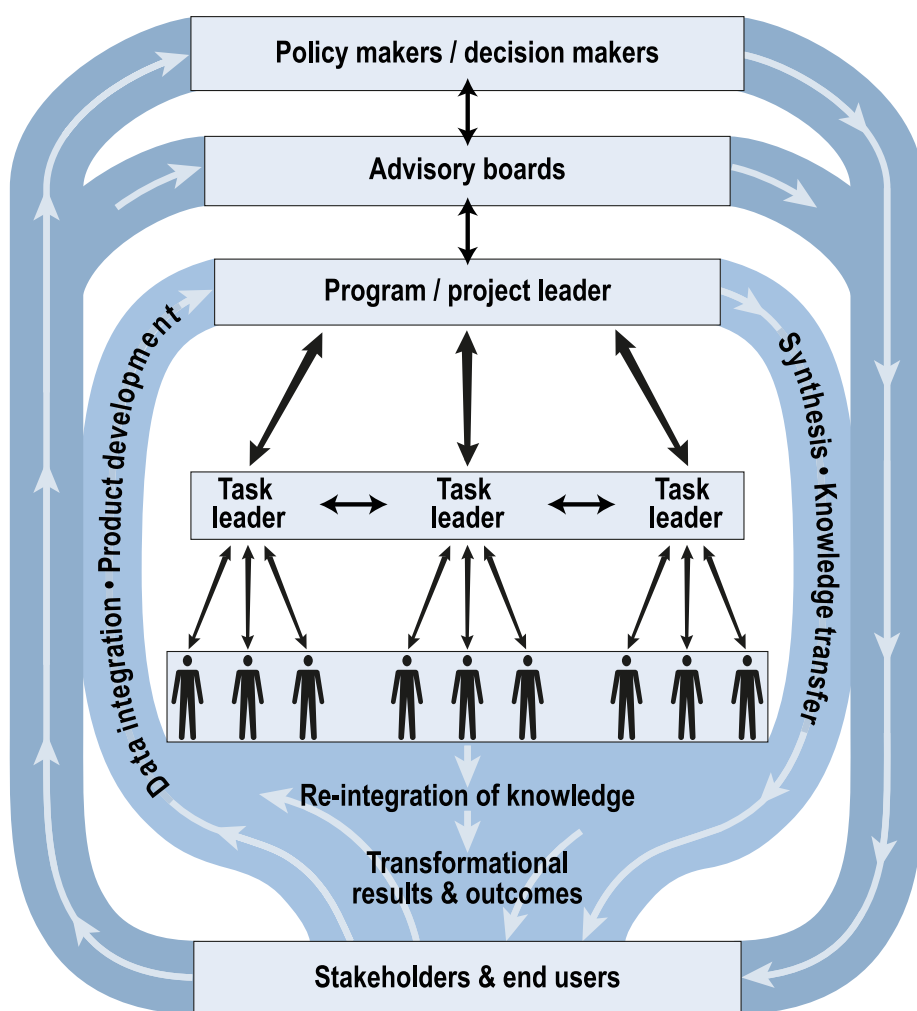
to local societal issues in the context of a national program, while also providing a platform for supporting relevant social science activities.

### Outcome-Driven Structure

The central goals of a TD OA program should be based on societal priorities that can be effectively addressed through scientific research, which together provide a clear and realistic path toward achieving well-conceived, specific outcomes. The central theme should be broad enough to engage the support of all participants, but specific enough to define a clear legacy outcome that is relevant and usable for stakeholders. It is from this foundation

that component activities and tasks are designed with clear roles and context.

A key driver for TD OA research is the need to improve forecasting tools to project future impacts of OA (Andersson et al., 2015, in this issue). Previous failures of the OA community to meet this challenge have (in part) been due to inadequate planning of an appropriate level of work detail before new data collection activities are initiated, impeding integration of results. Many large OA projects focus on development of system-scale conceptual or numerical models that require integration of large data sets from several disciplines. To achieve this integration, appropriate spatial and temporal



**FIGURE 3.** Organizational structure for a transdisciplinary OA program. Problem framing and team building are most effectively accomplished as an inclusive and collaborative effort among program and project leadership, participating scientists, advisory councils, stakeholders, and end users. Problem framing is an iterative process that evolves as new knowledge and outcomes are re-integrated into the activities of all participants. Graphics by Betsy Boynton, USGS

scales, resolution, coordination of all data collection exercises, and standardization of methods must be considered with the end goal in mind before pursuing data collection activities (Busch et al., 2015, in this issue). The appropriateness of, and methods for, scaling laboratory experiments to natural settings and applying these results as model input must also be carefully considered (Andersson

already exist in the United States and elsewhere, efforts are currently underway to enhance coordination of national and international data management systems for OA information, with appropriate data portals, sharing mechanisms, and synthesis tools (Garcia et al., 2015, in this issue). The structure and accessibility of data management arrangements should take account of user needs at a range of

from comparisons between expectations and actuality.

The US IWGOA recognizes the value of adaptive management for retaining flexibility to revise strategic research plans, as new discoveries require altering scientific directions. Mechanisms to accomplish this include holding a percentage of funding for unexpected but needed flexibility in science direction and offering value-added awards for outstanding new discoveries. UKOA also included opportunities for additional, small grant awards midway through the main program that were considered to be particularly cost-effective.

“ The overall success of [transdisciplinary ocean acidification] science depends on whether transformative results are achieved that not only advance the science but also affect public policy outcomes. ”

et al., 2015; Breitburg et al., 2015, both in this issue). Further challenges arise when projecting future societal and economic impacts through development of bio-economic models (Cooley and Doney, 2009). The Monaco Environment and Economics Group (established by the International Atomic Energy Agency's Marine Environment Laboratories and Scientific Centre of Monaco) sponsored a series of workshops to bring together scientists and economists from 20 countries to evaluate the potential economic costs of OA to fisheries, aquaculture, and tourism (Hilmi et al., 2013). Additional, region-specific workshops would help merge the perspectives and data needs of natural and social scientists in order to develop and apply community-relevant OA impact models.

Organizing, sharing, integrating, and synthesizing data sets, and building integrated interpretive products, are all essential for reaching OA goals at project and program levels. A data management system is therefore necessary and should be in place from the start. While such systems

levels, and may include the requirement for relatively nontechnical data products for management use and public access.

OA science has evolved very quickly during the past decade. Maintaining flexibility in research direction is, therefore, as important as focus on outcomes, so that management and science direction can be adjusted as appropriate in response to new knowledge and other developments. Adaptive management (Holling, 1978; NRC, 2004, 2011; Boesch, 2006) acknowledges that many management decisions must be made under conditions of uncertainty; if those decisions are framed as experiments, learning can occur when the results are carefully monitored and evaluated. For a TD OA program, adaptive management requires iterative linkages between partnership-based goal definition (taking account of both ecological and socioeconomic factors), explicit expectations (e.g., from modeling), prioritization and implementation of new data-gathering actions (through experiments and monitoring), and changed actions and plans arising

### Effective Communication

Every aspect of TD OA research requires connecting people through effective communications, with overall success reliant on trust-based interdependency of participants (Gray, 2008). In particular, program leaders should promote and reinforce intellectual stimulation (through divergent thinking, risk taking, and challenging standard methods) so that participants think beyond and across disciplinary boundaries, and they must encourage complementarity and synergisms. Leaders should also motivate participants to work productively together, yet with awareness that overuse of communication technologies (as a substitute for face-to-face discussion) can be counter-productive (Cummings and Kiesler, 2005).

Liaisons between advisory boards and project scientists should effectively interpret and transfer policy and management guidance (to scientists) and technical knowledge (to advisors). For TD OA, the diversity of discipline-specific languages can make this difficult. Recognizing this challenge, the OA community has successfully initiated communications training for scientists (Mathis et al., 2015a, in this issue). Early efforts focus on communicating technical information to non-technical audiences, particularly to media and publication editors. This approach could be expanded to stakeholder and

advisory board meetings, as well as facilitating knowledge exchange across organizational components.

Standardized terminology across different disciplines can reduce misinterpretation and misunderstanding while increasing the added value of information and effectiveness of information transfer. In particular, national and international OA data managers are developing standardized parameter definitions and vocabularies across disciplines (Lindstrom et al., 2012; Garcia et al., 2015, in this issue). Differences in OA experimental and data-collection methods have, unfortunately, added uncertainties to multistudy data interpretation (Kleypas et al., 2006; Gattuso and Lavigne, 2009; Yates et al., 2013). Best practices for OA methods (Dickson et al., 2007; Riebesell et al., 2010) and inter-laboratory comparisons (Bockmon and Dickson, 2015) have been developed by the international OA community to help standardize methods in order to enable better integration and comparison of results. Training workshops and inter/intra-program meetings provide the means to transfer such technical knowledge across tasks/disciplines while implementing improved methods as they evolve.

### Measuring Success

Traditional metrics for the progress and growth of OA science include publication outputs, database production, citation indices, meetings held and attended, and new funding secured. Additional metrics relevant to the TD approach include outreach and education tools (websites, videos, media highlights, training courses), surveys of stakeholder satisfaction, establishing timelines, and meeting deadlines for completing objectives.

The overall success of TD OA science depends on whether transformative results are achieved that not only advance the science but also affect public policy outcomes (i.e., contributing to real-world solutions). Such outcomes are likely to take several years to achieve, because they require shifts in cultural mindset


and changes in organizational practice. Nevertheless, TD-relevant metrics can be used to evaluate progress toward such long-term goals, based on markers of intellectual collaboration and integration (Stokols et al., 2003; Bergmann et al., 2005; Center for Ocean Solutions, 2012). Specific examples include:

- Creation of task forces to promote TD science
- Commitment from institutions by adding TD science to mission statements
- Funding and resources for implementation and support
- Active plans to address administrative hurdles
- Opportunities for face-to-face coordination meetings
- Altering participant tenure and merit review procedures to accommodate the time-consuming nature of collaborative research and publication

The use of such metrics would help overcome institutional barriers to the development and implementation of TD OA science. A TD-based evaluation strategy would also assist in embedding and engaging social scientists in OA research, and provide opportunities for cross training of students in order to grow a community of experts in merging the social and Earth science practices that will be required to find solutions for the global impacts of OA.

### CONCLUSIONS

Understanding and addressing the complex scientific and societal issues surrounding OA require TD science: the merged perspectives of experts from diverse disciplines. The OA community has already taken steps toward the TD approach at national and international levels; however, full integration of natural scientists, social scientists, economists, policymakers, and stakeholders remains a challenge. Impediments at the institutional level (including aligning agency missions and integrating funding sources) remain, but progress has been made in recognizing these issues

and formulating mechanisms to overcome them. Although TD projects are more complex to organize and may take longer to produce results, the outcomes achieved should be more directly applicable to solving societal problems, be embraced by a wider constituency, and ultimately provide transformative scientific and societal solutions for managing environmental change caused by OA. 

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