## Sustainable Oceans: From Policy to Science to Decisions

### a. Core Participants

| Name | Role | Affiliation (all at UC Davis) | Discipline |
|---|---|---|---|
| James N. Sanchirico | PI | Environmental Science & Policy | Env. & Resource Economics |
| Marissa L. Baskett | Co-PI | Environmental Science & Policy | Conservation Biology |
| Louis Botsford | Co-PI | Wildlife, Fish, & Conservation Biology | Marine Ecology |
| Alan Hastings | Co-PI | Environmental Science & Policy | Applied Math/Pop. Dynamics |
| Nann E. Fangue | Co-PI | Wildlife, Fish, & Conservation Biology | Marine Ecology/Physiology |
| Tessa Hill | Participant | Earth & Planetary Sciences/Bodega Marine Lab (BML) | Marine Biogeochemistry |
| John Largier | Participant | Environmental Science & Policy/BML | Coastal Oceanography |
| Rick Grosberg | Participant | Evolution & Ecology | Marine Ecology/Evolution |
| Michael Springborn | Participant | Environmental Science & Policy | Env. & Resource Economics |
| Cynthia Passmore | Evaluator | Education | Science Education |

### b. Theme, Vision and Goals

One of the NSF grand challenges for ocean science is an evaluation and quantification of the "effects of natural and anthropogenic change on marine ecosystems" in order "to sustain, for generations, the biodiversity and productivity we increasingly depend on in the oceans." At the same time, the primary U.S. agency in charge of monitoring and regulating activities in the ocean, the National Oceanic and Atmospheric Administration (NOAA), and other federal and state resource management agencies, have an unmet and growing demand for quantitatively trained scientists [1]. In addition, the paradigm of resource management is shifting away from the traditional focus on single fisheries and moving toward a holistic ecosystem approach [2-4]. The new paradigm accounts for a) interactions among different species, e.g., predation, competition; b) variability in the environment in space and time; c) synergistic and antagonistic relationships among socio-economic sectors and uses; and d) interactions between all of these factors [3, 5-7]. This approach, termed ecosystem-based fisheries management (EBFM), has been adopted by NOAA, the European Union Fisheries Commission, and many other management agencies around the world. However, development of the models and procedures to evaluate and quantify the effects of EBFM are in their formative stages.

The ***Sustainable Oceans: From Policy to Science to Decisions*** (SOS:PSD) NRT focuses on three frontier and cross-cutting research themes that are essential elements of EBFM:

**Theme 1.** **Scaling up**: Aggregation and integration of data from multiple sources and from the individual to the ecosystem to aid in decision-making.

**Theme 2.** **Data-model integration**: Integration of data and models to inform management design and assessment of impacts.

**Theme 3.** **Decision-making under uncertainty**: Valuation of different types of information for a range of decisions that are fraught with various levels of uncertainties.

Addressing these challenges requires the development of novel models and methodologies that integrate approaches from the natural and social sciences.

**We propose to train the next generation of quantitative marine scientists under a new paradigm that *begins with the decisions facing policy makers* to generate use-inspired research questions across ecology, conservation biology, economics, geology, physiology, biogeochemistry, and oceanography.** We envision future generations of researchers, policymakers, and educators seamlessly integrating multiple types of information across multiple scales to improve the scientific basis of decision-making in the management of natural resources. These leaders will have the breadth of knowledge and skills necessary to link seamlessly natural and socioeconomic questions in the emerging field of ecosystem management.

The SOS:PSD NRT has five major goals with both immediate and long-term impacts:

**Goal 1:** Transform the science that underpins decision-making in the management of ocean resources by integrating use-inspired science across diverse disciplines to improve the integrated assessment of current and proposed policies.

**Goal 2**: Recruit, train, inspire, and mentor a diverse, new generation of STEM scientists to understand the implications of uncertainty when complex information across multiple scales, from data-rich to data-poor situations, must be combined for effective decision-making.
**Goal 3**: Extend our novel paradigm into graduate training in relevant disciplines in marine science, including the interdisciplinary Graduate Group in Marine Science that is currently midway through the approval process at UC Davis (with anticipated enrollments by Fall 2018).
**Goal 4**: Broaden participation of under-represented students from natural resource-dependent communities (e.g., tribal nations, rural coastal towns), and recruit, train, and retain students to develop technical and professional skills for careers within and outside academia.
**Goal 5**: Undertake evidence-based assessment and disseminate novel training elements and experiences, including our approaches to broadening participation of underrepresented communities in the multidisciplinary fields of ecosystem management.

***Our paradigm to interdisciplinary training moves the focus on policy to the front-end of the research enterprise, when questions are asked and hypotheses formed.*** We implement our approach by immersing trainees in the complexity of policy-making. Trainee activities include internships with science and policy organizations, basecamps (week-long workshops with decision-makers and stakeholders organized around marine management issues), and fieldtrips to resource dependent communities to engage with stakeholders and community leaders. We also develop new graduate electives to broaden and strengthen our curriculum, including a new transdisciplinary course whose basis is a **causal chain. The casual chain** extends from a policy goal to a management intervention to the scientific information needed to assess the ecological, economic, and social impacts of the policy (Fig. 1). We have deliberately chosen this training approach because the *modus operandi* of considering *ex post* the policy and broader impacts of research often leads to frustration from scientists that policy-makers are not "using" their research.

An often-cited remedy for this perceived disconnect between these two communities is to improve the communication skills of scientists. While improving communication skills is a useful endeavor and central part of our training program, we believe the reliance on these training elements addresses the symptoms and not the fundamental driver of disconnect between scientists and policymakers. We hypothesize that (1) the fundamental cause of the disconnect is that disciplinary (and interdisciplinary) research questions often do not align with the questions policymakers are asking (see, e.g., [8]), and (2) researchers rarely have the wide-angle lens necessary to understand how their research combines with all of the other science necessary to address policy questions and assess the performance of management. ***We will explore both hypotheses in our training program using the causal chain model, including how to integrate use-inspired science from different fields into a coherent narrative to aid decision-making***.

Developing the skills to understand how research from different fields can best be assembled to inform policy decisions is especially critical with the advent of ecosystem-based fishery management and the inherent increase in complexity associated with evaluating and assessing policy interventions across an ecosystem. ***Our learning model, however, is much more general than marine science***. In fact, the causal chain model can easily be transferred to students and researchers working on forest conservation, pollution reduction, water management, and, more generally, any policy intervention (e.g., education reform). To increase the scalability of our model, we will make both our methods and the evaluation of them available to the broader community, both on and off campus that would be interested in improving the interface and discourse between scientific research and public policy.

Our SOS:PSD NRT seamlessly integrates into the Coastal and Marine Science Institute (CMSI) at UC Davis, as many of the participants on this proposal are in leadership positions in CMSI (R. Grosberg, Director; T. Hill, Associate Director. for Academic Programs; J. Sanchirico, Associate Director for Policy; and J. Largier, Associate Director for Research). CMSI plays a pivotal role at UC Davis in marine science education with the undergraduate major in Marine and Coastal Science (providing opportunities for NRT trainees to gain teaching and mentorship experience) and with the proposed interdisciplinary graduate program in Marine Science (PhD currently under campus review). Although SOS:PSD represents only a part our new PhD program in marine science, the NRT will provide a foundational model for the program over the long term: first, by integrating the **causal chain** model into the curriculum; second, through the integration of data and modeling; and third, by building a model and pipeline that will broadly enhance the

recruitment, retention, and mentoring of under-represented groups in quantitative resource management and policy.

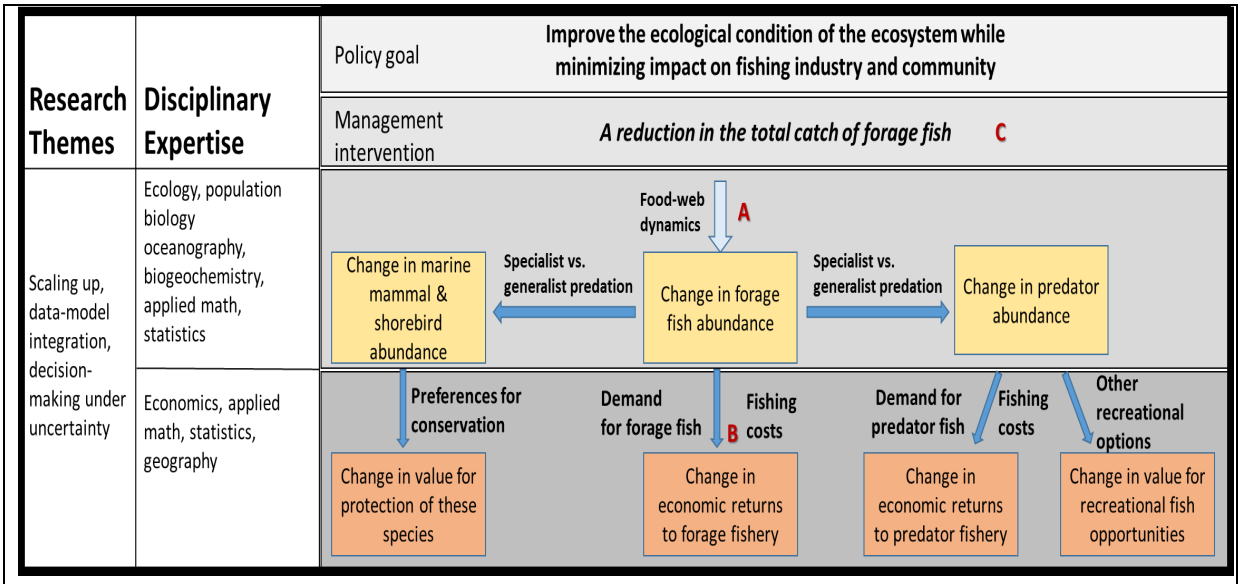


**Figure 1**: An ecosystem-based fishery management **causal chain** on forage fish that highlights the interdisciplinary nature of the enterprise, cross-cutting themes, and basis of our training approach. Note: Each arrow represents a step in the socio-ecological process that may not be well understood and serves as a locus for posing a research question, as does the measurement of the ecological and economic endpoints in the boxes. For example, **A** highlights the ecology needed to address whether the reduction in fish catch will result in greater fish abundance; this depends on degree of top-down or bottom-up control in the food chain. **B** highlights that whether the change in forage fish abundance leads to a change in the economic returns to the fishery depends on the prices of fish (demand for the forage fish and other possible substitute products) and the costs to fishing, which depends on fishermen behavior. **C** highlights how different management interventions could achieve the goal, including the designation of marine protected areas (e.g., closing areas off to fishing) and each management intervention will have its own causal chain and set of scientific questions.

CMSI plays a critical role in the basecamps, internships, fieldtrips, and partnerships of our program SOS:PSD. CMSI, for example, has a proven track record of assembling scientists, leaders of government agencies, and stakeholders in a neutral forum (e.g., workshops) to discuss the state of the science and the scientific needs of decision-makers with the goal of developing a mutually beneficial research agenda. In addition, CMSI and CMSI-affiliated faculty (Baskett, Botsford, and Hastings) are partnering with CA Department of Fish and Wildlife (CDFW) and CA Ocean Protection Council to advance the science of marine protected areas (see section d3) by jointly mentoring with CDFW scientists three post-doctoral fellows – this is an example of SOS:PSD's approach to co-production of knowledge [9].

In the fields represented by the SOS:PSD, students from natural resource-dependent communities (e.g., tribal nations in Northern California, rural and remote coastal towns) are especially under-represented. Because of this under-representation, there is a critical loss of intellectual capital and many cultural and social problems are neither defined nor addressed by the scientific and management communities. At the same time, these students are more likely to engage in research that is relevant to their communities. The SOS:PSD NRT seeks to address this underrepresentation by taking a two-pronged approach focusing on making short-run inroads and long-run structural changes to recruitment, retention, and mentoring (Section g). In the short run, for example, we are partnering with California State University's (CSU) Council on Ocean Affairs, Science and Technology (COAST) to develop a novel year-long UCD CMSI-COAST Scholars program (see Partnership letters). The program will involve three CSU Master Students in our NRT activities each year (CSU has 23 campuses, 17 of which are Hispanic-Serving Institutions). In the long-run, we will fully integrate natural resource-dependent communities into all aspects of our program, including participating in the research (e.g., Yurok tribe), basecamps, and

fieldtrips. Our NRT trainers will also work with UC Davis leadership who are reaching out to underrepresented minority groups (URMs) at CA community colleges to highlight the undergraduate and graduate-level training in marine and coastal science at UC Davis as a means to develop a pool of applicants to our NRT. UC Davis is expected to earn U.S. Department of Education Hispanic Serving Institution (HSI) designation by 2018-2019, when 25 percent of our undergraduates will be of Hispanic origin. Together, our short-run and long-run strategy will change the URM seascape in research and policy-making in marine science.

To build and advance the professional skills of graduate students (leadership, mentoring, project management, communication, and ethics), our training program is fully-integrated with *GradPathways. GradPathways* is a nationally-recognized professional development program for graduate students and postdocs, coordinated by the UC Davis Office of Graduate Studies (see Section c. 1.10 for details and Facilities). In consultation with his/her own mentoring (section g.3), each trainee will also construct an Individual Development Plan (IDP) — using myIDP, a website created by the American Association for the Advancement of Science — that will be updated throughout the trainee's education.

## c. Education and Training

Dating back to its origin as a land grant institution, UC Davis is, at its core, an interdisciplinary university with research spanning basic and applied science across both traditional (e.g., Evolution and Ecology) and non-traditional (e.g., Wildlife, Fish, and Conservation Biology) departments and graduate training structures. Our PhD graduate training consists of departmental programs, such as Agricultural and Resource Economics, and graduate groups that cross departmental and college boundaries. For example, the Graduate Group in Ecology has over 120 faculty participating from three professional schools, four undergraduate colleges, and 16 departments. The new Graduate Group in Marine Science will encompass a similar degree of intellectual diversity. We anticipate that the majority of our PhD trainees will enroll in Marine Science or existing graduate programs in Agricultural and Resource Economics, Ecology, Population Biology, Geology, or Applied Mathematics.

**Table 1**: Training Elements and Learning Outcomes

| | **Learning outcomes** | | |
|---|---|---|---|
| **Training elements** | Policy to Science | Science to Decisions | Career skills |
| Resource Management Fieldtrip* | ✓ | ✓ | ✓ |
| Internship in Science and Policy* | ✓ | ✓ | ✓ |
| Basecamp with Decision-makers* | ✓ | ✓ | ✓ |
| Short-term Visiting Scientists* | ✓ | ✓ | ✓ |
| Causal Chain Course* | ✓ | ✓ | ✓ |
| Marine Science & Policy Course* | ✓ | ✓ | ✓ |
| Data-model integration course * | | ✓ | |
| Research symposium* | | ✓ | ✓ |
| Trainee CSU presentation* | | | ✓ |
| NRT Thesis Chapter* | | | ✓ |
| GradPathways and myIDP | | | ✓ |
| * New training elements developed for this NRT. Dark gray and checks = significant and direct contribution to learning outcome; light gray = indirect contribution, white = NA. | | | |

To achieve Goals 1 and 2 of SOS:PSD and building on the interdisciplinary culture at UC Davis, our **learning outcomes** are (1) *Policy/Science interface*: to acquire the expertise to (a) pose incisive research questions that follow from policy implications and (b) understand how research from different fields fits together to inform policy decisions; (2) *Science/Decisions interface:* to attain a rigorous understanding of the opportunities, challenges, and limitations of combining data from multiple sources and scales, and integrating data and models to inform decision-making in the presence of uncertainty; and (3) *Career Skills*: to build cross-cutting career skills, such as time and project management, mentoring, effective collaboration leadership, ethics, writing techniques, and public speaking to a range of audiences(Table 1).

c.1 **Training model**. We will achieve these learning outcomes by combining several novel approaches to STEM graduate training that emphasize problem formulation and solving, rather than prioritizing the acquisition of technical skills *per se*. The latter skills will be developed in the respective graduate programs of the trainees. Our training program will elucidate (1) the views and perceptions of stakeholders (***fieldtrips***), (2) the questions policymakers are addressing today and in the future (***basecamps***), (3) the activities of federal, state, and non-governmental organizations

(***internships***), (4) the creative side of research through extended interactions with natural and social science researchers working on ecosystem management (***short-term visiting scientists***), and (5) the skills necessary to communicate science to interdisciplinary academic and non-academic audiences (***fieldtrips***, ***research symposium, basecamps, internships, trainee presentation at CSUs***). We supplement this immersion in the "soft" aspects of use-inspired research with new courses developed specifically for the NRT (e.g., a marine science and policy course, a causal chain course, and a data-model integration course). These courses will complement the trainee's PhD graduate program requirements; however, they will not represent additional time to degree as these courses have been designed so that they can count as electives in each of the participating graduate programs. Finally, the UC Davis ***GradPathways Program*** will be integrated into each trainee's course of study to provide the foundational professional skills necessary to be successful in a range of careers – skills that will be refined by participating in our basecamps, internships, fieldtrips, and research symposium. Trainees will also develop leadership skills throughout the program as older cohorts will mentor younger ones and will also take a leadership role in planning the fieldtrips, basecamps, and selecting short-term visitors.

The timeline for the program balances our trainees' respective graduate program training with the priority of developing skills within the SOS:PSD NRT program as early as possible (Fig. 2). With many of the new activities scheduled for the summer between the students' first and second year of their graduate programs, we are also minimizing potential conflicts with their graduate training. The NRT coursework will also contribute directly to their NRT thesis chapter and more generally, their participation in the NRT activities will help reduce the gap between coursework and dissertation research, as the program components and mentoring will help trainees develop their use-inspired research thesis along the way, rather than after completion of their coursework. UC Davis students are expected to complete their PhD programs within four-six years, such that the first cohort will be finishing as the last is arriving. Following our experiences in previous IGERTs, we will coordinate recruitment and admissions to the SOS:PSD NRT with admissions to the relevant graduate programs on campus, so that PhD trainees will receive a comprehensive multi-year support package, including other campus Fellowships, research and teaching assistantships, and SOS:PSD NRT funding for their second year.

NSF funding will support five PhD trainees per year over five years and the UC Davis Office of Graduate Studies along with the College of Biological Sciences will support an additional trainee per year for five years (see Institutional Letter of Support). In addition to the 30 funded PhD trainees over the course of SOS:PSD NRT, we expect participation of ~15 CSU Master's students via our new Scholars program (basecamps, fieldtrips, and research symposia), and ~50 non-NSF funded trainees from other graduate programs on campus who will participate in all or some of the components of the training (new courses, visiting scientists). The Scholars will receive an honorarium and travel funds to offset their costs for participating in the basecamps, fieldtrips, and research symposium (see Section g and Institutional Letter of Support). The honorarium offsets potential costs for URM students (e.g., lost work hours) that might reduce their participation in the Scholars program while at the same time adding prestige to the program to attract a diverse and large applicant pool.

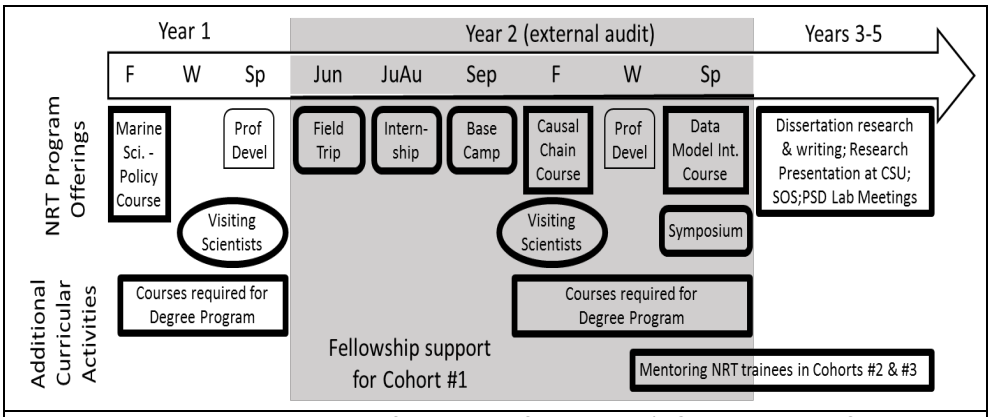


**Figure 2**: Timeline highlighting the first cohort of 6 trainees (NSF support 5, UC Davis support 1). The pattern repeats for the four subsequent cohorts. Ju=June JuAu=July-August, S=September, F=fall qtr., W=winter qtr., and Sp=spring qtr.

Trainees will begin the SOS:PSD program in their first year with a one-day orientation immediately prior to the start of the academic year, enrollment in our Marine Science and Policy (MSP) course (fall qtr.), and participation in activities throughout the year surrounding the Visiting Scientists Program and

other community events at CMSI and the UC Davis Bodega Marine Lab (BML). At the close of the orientation, trainees will begin to develop their myIDP in consultation with the UC Davis Internship and Career Center that run workshops on the tool. The MSP course is offered in the fall so that trainees can develop the language and understanding of marine science in the context of resource management at the outset of their graduate training.

The majority of training activities occur during the second year of the program, when trainees are funded by SOS:PSD and have already acquired a base of disciplinary knowledge from their respective graduate programs in year one. However, the trainee program does not end in year 2: more senior cohorts will continue to mentor the newer cohorts, participate in visiting scientist events and recruitment activities, and contribute to the intellectual development of basecamps and the causal chain course, and will be actively mentored by their dissertation committee and the NRT trainers through collaboration on their thesis chapter. Professional development activities will also continue throughout their academic careers. The timing of our main training elements fits nicely with the timeline for NOAA Fellowships in population dynamics or marine resource economics that fund years three and four of a PhD; UC Davis PhD students have been very successful in receiving these fellowships (with advisors Sanchirico (2), Botsford (3), and Baskett (3)).

c.1.1 **Resource management fieldtrip**. The week-long trip will introduce SOS:PSD trainees and CMSI-COAST Scholars to the technical, cultural, biological, economic, and institutional forces woven into the fabric of resource-dependent communities in California and beyond. Visits will be arranged with a wide spectrum of marine resource stakeholders, including fishermen, fish processors, oyster farmers, recreational fishing interests, federal, state, and local government field officers and scientists, and non-governmental organizations. The exposure to the diversity of interests will be invaluable in immersing trainees in the broader context that connects individual research to the policy process. We will also use these opportunities to foster the relationships that can springboard internships for our trainees and to reach out to URMs in these communities. In addition, the fieldtrip will expose students to career pathways in government agencies and the private sector, enable them to make connections with key staff from potential employers, and, for CMSI-COAST Scholars, provide an opportunity for interactions with prospective doctoral advisors in our SOS:PSD, supporting our commitment to the broadest feasible participation. The fieldtrip will occur in June between the first and second years of training, minimizing the impacts on coursework and overlap with graduate group programming. In addition to intellectual benefits, the field trip will help build community within the cohort of trainees and faculty mentors.

c.1.2 **Internship.** A required, fully supported internship will bridge university training with the needs of our partners by providing first-hand experience to trainees in addressing real-world problems. Internships bring substantial, and often long-lasting, benefits to non-academic partners by providing ongoing access to the best available science, but also access to a pool of experienced, well-trained future employees and colleagues. We will develop a comprehensive menu of internship options (see Partnership letters), covering scientific components of policymaking in marine science (e.g., CA Ocean Protection Council, NOAA Southwest Fisheries Science Center) and the incorporation of science into policy decisions (e.g., UC Center Sacramento; Resources for the Future, Washington, DC). Following the fieldtrip, the eight-week internship will occur during the summer (July-August) between the trainee's first and second year and will be covered by their stipend. Program Coordinator Dr. Carole Hom, who has extensive experience implementing three previous IGERTs at UC Davis, will partner with the UC Davis CMSI Executive Director Dr. Shauna Oh and UC Davis Internship and Career Center (ICC) in facilitating internships (see Section f). Specifically, the ICC will support trainees through one-on-one advising as they identify professional goals, explore internship sites, and develop application materials. We have budgeted funds to cover trainee relocation costs during their internship, as needed.

c.1.3 **Basecamp with decision-makers**. Annually, we will hold a week-long SOS:PSD basecamp that will focus around a marine resource management issue with decision-makers, including colleagues from private-sector interests, non-governmental organizations, and governmental agencies, and community-leaders. Each basecamp will bring together a diverse set of stakeholders to discuss the trade-offs involved with a management goal. For example, the basecamp for year 1 could focus on monitoring and assessing the performance of Marine Protected Areas (see section d. Major Research Efforts) or on the development of fish and shellfish aquaculture, both in state and federal waters.

The basecamps provide an immersive forum for our trainees to network with professionals in marine resource management and provide the background and focus for the causal chain course during the subsequent academic year (see discussion below). That is, the basecamps, held a week before the fall quarter begins (end of Sept.), will be used to develop the policy topic for the casual chain course that will follow the basecamps in the first quarter of their second year. *CMSI-COAST Scholars will be participating in the basecamps very early in their 2nd year of a two-year master's program, which is the point when their master's research projects are being defined. As such, their participation will help them develop use-inspired research projects and broaden their network with ocean and coastal policy leaders that could help improve the broader impact of their research. Overall, the integration of the Scholars is a means to strengthen intellectual ties between faculty at the two institutions, create a pathway for recruiting diverse California State University students to UC Davis, and broaden the impact of the NRT* (see Partnership Letters). With extensive trainee input, especially from the older cohorts, the leadership of the SOS:PSD NRT will be responsible for developing the topic and agenda and inviting participants. We will hold the basecamps on the main UC Davis campus to take advantage of our proximity to the state capitol, and funds are budgeted to help defray travel costs of invited guests.

c.1.4 **Short-term visiting scientists** (seminar, salons). While the fieldtrip, basecamps, and internships immerse the trainees in the marine resource management seascape, the "art" of successful STEM research can remain elusive. To that end, we incorporate a short-term visiting scientist program that will invite three scientists in each of the winter and spring quarters during each year of the training program. The scientists will be invited to give a scientific and public lecture on campus and will be housed during their stay in the office space of the CMSI. During their stay, we will hold "salons" for the trainees, faculty, and other interested graduate students on campus that combine a casual dinner at CMSI with an informal discussion led by our visitor on how they develop research questions and what leads to their success. CMSI already has experience with the salons and they have proven to be a highly effective forum for students, faculty, and guests to interact and discuss non-technical aspects of research and career development. The visitor will stay a week on campus, and will have additional time allocated to mentor our trainees in one-on-one meetings that will give the trainees feedback on their research and career plans. The selection of the visiting scientists will follow the theme of each year's **basecamp** and the **causal chain** course. To broaden the reach of the program, the lectures by the visitors will be video-captured and freely accessible online to our *CMSI-COAST* Scholars and colleagues around the world.

c.1.5 **1-day research symposium.** Starting in year 2 of the NRT, we will hold an annual one-day research symposium on the UC Davis campus to highlight the research of NRT trainees and other graduate students at UC Davis, and early career scientists working on coastal and marine issues. The workshop will be advertised broadly and open to early career scientists from other universities and government agencies. The workshop will consist of an invited keynote lecture, 20-minute presentations for more-developed research and 5-minute presentations on research/thesis ideas. The egg-timers are especially for our NRT trainees who are developing thesis ideas. We will also have a special presentation and poster session dedicated to research from CSU Masters projects, including but not limited to our CMSI-COAST Scholars. The symposium will be at the end of spring quarter (late May) to accommodate CSU master students who will be finishing up their research in year 2 of their programs, and before NRT trainees begin their dissertation research full time in year 3 of our program.

c.1.6 **NRT Trainee presentation**. NRT Trainees will be required to give a research talk at a CSU minority-serving institution once during years 3-5 of their research program. The funds to cover travel and lodging will be provided by the NRT such that there are no costs to the CSUs while hosting our trainees. These talks will provide the NRT trainees with valuable experience that will help prepare them for academic or non-academic careers. NRT trainees will be ambassadors for our program, valuable resources for CSU master students interested in learning more about PhD programs, and provide an important link between SOS:PSD and CSU programs in marine and coastal science.

c.1.7 **Novel coursework for the NRT**. We will develop a new three-course sequence that spans the first and second year of the training program. In the first quarter of the first year, PhD students selected for the traineeship, whose funding starts in year 2, will take a marine science and policy course that provides the basic set of knowledge required to understand the role of the different disciplines in marine resource

management. In the first quarter of their second year, during their traineeship, the trainees will take a causal chain course where they will develop a causal chain. The third course on data-model integration will be in the spring quarter of the second year. All of these courses will be part of the NRT trainee's PhD program (electives) and open to the graduate student community on campus beyond those supported with SOS:PSD funds. These courses will remain part of the graduate curriculum after the SOS:PSD program.

(1) The **marine science and policy** course will provide the fundamental background across the full spectrum of relevant disciplines essential for the development, assessment, and implementation of ecosystem-based fisheries management programs. The course will be taught by UC Davis faculty experts, with lectures on physical oceanography (Largier), population dynamics (Botsford and Hastings); marine ecology and evolution (Baskett and Grosberg), climate change and marine systems (Fangue, Hastings and Hill), and resource economics (Sanchirico and Springborn). Once this new interdisciplinary course has been established, it will be a permanent part of the curriculum of the new PhD program in Marine Sciences (anticipated in 2018). Based on the current interest in marine sciences, we anticipate ~15-20 students per year in the course, including the 6 NSF-funded trainees.

(2) The **causal chain course** will train students in deriving research questions from the needs of management problems, and, by example, demonstrate how to build large-scale interdisciplinary research projects and teams. The class will develop the chain to highlight the set of research questions. For example, in Fig. 1, the links between the boxes represent steps in the socio-ecological process that may not be well understood and serve as a locus for posing research questions, as does the measurement of the ecological and economic endpoints in the boxes. Once the students identify all of the pieces of natural and social science necessary to assess the performance of the management intervention, student–faculty teams (two-three students per team) will be formed. The teams will be responsible for assembling the relevant literature and summarizing the current state-of-the-art, determining what types of data are used in the analysis, the level of certainty with respect to the direction of the change, and identifying critical gaps in current knowledge. Faculty will serve as active mentors to the students, helping them navigate the relevant literature. The groups will present their findings to the class. Based on prior experience with a similar course (the development of Fig. 1 was part of a one-off course on forage fish management taught by PI Sanchirico), we anticipate a class size of ~20 students, including the six NSF-funded trainees. The class will also write a white paper (final class project), guided by the faculty mentors, that combines the causal chain, literature review, and gap analysis as a way to identify and prioritize a research agenda. The white paper will be submitted for publication in a peer-reviewed journal and will be developed by the trainees into shorter communication pieces (blogs, tweets, and 1-page summaries) that will be distributed to relevant sets of stakeholders.

(3) The **data-model integration** course will focus on bringing the key aspects of the Causal Chain process (e.g., "dose-response" curves) to data. The course will provide training on fitting linear and nonlinear dynamic models to data. Topics in the course will include: (1) basic statistical background, including the Bayesian approach to estimation (e.g.,[10]); (2) commonly used numerical approaches to model fitting, such as BUGs, AD Model Builder and related software in R [11]; and (3) examples of commonly used numerical approaches in various specialties (e.g. stock assessments in fisheries, [12]). The course will be open to graduate students from a number of fields and degree programs. Based on experiences with previously taught courses with similar material, expected enrollment is ~20 students, including the six NSF-funded trainees.

c.1.8 **Disciplinary PhD training at UCD.** The SOS:PSD NRT program will formalize, expand the scope of, and bring broader visibility to efforts that have been underway for several decades at Davis: training highly-qualified and quantitatively oriented marine scientists. Past students have found opportunities in academic institutions, NOAA science centers, state agencies, and conservation organizations.

**Table 2**: Example of Disciplinary Graduate Training.

| **Marine Ecology** | **Natural Resource Economics** |
|---|---|
| ECL 200A/B: Principles and App. of Ecological Theory | ARE 200A/B/C: Microeconomic Theory |
| ECL 231: Mathematical Methods in Population Biology | ARE 202A/B/C: Applied Microeconomics |
| ECL 214: Marine Ecology | ARE 240A/B/C: Econometrics |
| ECL 208 Issues in Conservation Biology | ARE 254: Dynamic Op. with Economic Applications |
| WFCB 262: Advanced Population Dynamics | ARE 277: Natural Resource Economics |

Because we are drawing from multiple graduate programs, there is no universal formula for a typical NRT PhD course of study. Table 2 provides examples using marine ecology and natural resource economics to highlight the quantitative training available on campus, and courses where the NRT themes are already emphasized. In addition to these courses, students can take other relevant electives, including ocean and coastal policy (Sanchirico), decision-making under uncertainty (Springborn), science communication (Hill), physiological ecology (Fangue), and summer session courses on toxicology, global change ecology, and oceanography at the UC Davis Bodega Marine Laboratory. Overall, the SOS:PSD model for producing top interdisciplinary thinkers is for trainees to develop deep and rigorous disciplinary expertise while immersing themselves in the activities and courses proposed as part of this program.

c.1.9 **SOS:PSD NRT Thesis chapter.** Building on the success in previous UC Davis IGERTs that also linked a dissertation chapter to the program, each trainee will complete a dissertation chapter that is use-inspired and emphasizes how their research fits into the design or assessment of a policy question. The research will be mentored by SOS:PSD faculty, the student's dissertation advisor, and other trainees through quarterly SOS:PSD lab meetings, which will start in the trainee's 3rd year. These lab meetings will consist of trainees presenting their research to groups of fellow trainees, faculty, and other colleagues. We will align these lab meetings to coincide with the stays of our **short-term visiting scientists.**

c.1.10 **GradPathways, Ethics Training, and myIDP.** The UC Davis *GradPathways* program specifically addresses the need to broaden support for diverse career pathways beyond graduate school [13]. Its framework for professional development builds on eight essential core competencies, including success and socialization in your graduate program, ethics, writing and publishing, presentation skills, teaching and mentoring, leadership and management, scholarly integrity and professionalism, career exploration, job searching and networking, and wellness and life balance. *GradPathways* offers tiered programming for the different stages of the graduate and postdoctoral experience; SOS NRT trainee involvement will focus on the introductory tier, emphasizing the areas of success and socialization, writing, ethics training, and presentation skills (see Facilities). Over 150 workshops, seminars, and panel discussions are offered throughout the year. Trainees interested in pursuing academic careers will be encouraged to apply to the UC Davis Professors for the Future program, which, through mentorship, training, and workshops, prepares graduate students for successful academic careers in research and teaching. While we will encourage our trainees to participate in *GradPathways* activities throughout their studies, we will require trainees to actively participate in their 2nd year in the Responsible Conduct of Research series that includes sessions on responsible authorship and mentoring, intellectual property, research misconduct, and peer-review. SOS:PSD will also support a distinguished speaker in the *GradPathways* seminar series in the spring quarter in each year of the grant. (e.g., Dr. Kerry Ann Rockquemore, President and CEO of the National Center for Faculty Development and Diversity). These lectures will be open to the UC Davis community.

In consultation with their own mentoring team, each trainee will construct an individual development plan (IDP) using myIDP, a website created by the American Association for the Advancement of Science. Annually, each trainee, along with their mentoring team, will refine and update the IDP as part of required progress reports in their individual graduate programs. The SOS NRT academic coordinator, Dr. Carole Hom, will track participation of the trainee in GradPathways events and the development and refinement of myIDP.

c.2 **Certificate of completion of SOS:PSD training**. The leadership of the NRT will collaborate with the Office of Graduate Studies and relevant graduate programs to develop a graduate certificate awarded to students who complete all of the SOS:PSD training elements (c1.1-c1.10). The certificate will be available to PhD students, including but not limited to NRT Trainees who fulfill the necessary requirements. Certificates are the best mechanism available in the UC system to create recognition across multiple graduate programs for students who complete a program such as our NRT that falls outside of their respective graduate programs.

c.3 **Innovative aspects of the training model.** The innovative and transformative aspects of our training program are the equal emphasis on the "soft" and "hard" aspects of use-inspired science; the

development of the causal chain course as the basis of interdisciplinary training, both in terms of the science and teamwork; the exploration of explicit hypotheses regarding the challenges integrating scientific research, communication, and policy; the multiple linkages with under-represented communities (fieldtrips, basecamps, research activities) as a means to develop stronger connections that lead to greater numbers of URMs participating in marine science, and the integration with the *GradPathways* program at UC Davis. Through our program, trainees from diverse fields will develop strong disciplinary skills, as well as a collective understanding of ecosystem-based management and the scientific needs of policymakers.

### d. **Major Research Efforts**

We provide three sample research efforts currently ongoing at UC Davis that will integrate into our curriculum to achieve our learning outcomes and goals. The research efforts will be utilized in the **Marine Science and Policy course**, **basecamps** and **Causal Chain** course, and will provide training data sets for use in the **Data-model Integration course**.

Our first research effort on multiple stressors builds on two ongoing projects at UC Davis that scale up individual-level impacts to population-level effects for improved conservation of listed species (green sturgeon in CA) and the recovery of commercially viable wild and farmed resources *(*e.g., red abalone). Both of these projects highlight how our NRT research efforts are fully-integrated with stakeholders who are existing or potential partners in our fieldtrips, basecamps, and internship program.

Our second effort builds on an NSF Coastal SEES grant (Sanchirico) that is utilizing vessel monitoring system (VMS) data to develop novel models of fishermen behavior to better predict how fishermen will respond to management interventions. Similar to the multiple stressor research, where the innovations are in scaling up, the VMS data are at the vessel-trip level, and for policy assessment we need to scale up to the fleet. Fleet-behavior modeling is a key part of almost all marine management assessments, as it not only directly contributes to the socioeconomic impacts of the intervention but also the ecological outcomes (fleet modeling would fit under point B in Fig. 1).

Our third research effort highlights the role of data–model integration and decision making under uncertainty. Researchers at UC Davis have played an important role in the implementation of a network of marine protected areas (MPAs) along the California coast (Largier, Botsford, Sanchirico, and S. Morgan). The current focus is on assessing the performance of the network using monitoring data (Botsford, Baskett, Hastings) in an adaptive management context. Modeling efforts play a critical role in predicting the expected population responses to MPAs so that the data can be compared to expectations (MPAs are another intervention that would have its own causal chain with an explicit focus on spatial modeling, point C in Fig. 1).

Collectively, our three research efforts highlight to trainees the art and science of SOS:PSD research, with an emphasis on the three themes (scaling up, data-model integration, decision-making under uncertainty). At the same time, these research efforts are at the cutting-edge of ecosystem management. Each of the projects require disciplinary expertise, and the causal chain course will provide students with insight in how to integrate this science in large scale, transdisciplinary settings and how disciplinary research fits into a landscape of research necessary to assess marine policies.

d.1 **Multiple interacting impacts: scaling up from individuals to populations** Given the scope of global environmental change—including climate change, harvest, pollution, and habitat modification [2, 14]—nearly all managed species and systems face multiple and often interacting forces of transformation. Accounting for the interactions between impacts is essential to developing actionable information that can underlie management decisions under global change. Local managers can protect the capacity for populations and communities to respond to such impacts by mitigating locally-controllable stressors (e.g., habitat degradation, pollution, freshwater runoff, nutrient loading) which may interact synergistically with global-scale changes (e.g., climate change, ocean acidification; [15, 16]). Much of the data on organismal responses to stressors is at the individual level (e.g., [15]), in the form of physiological measures (*i.e.*, vital rates such as growth, fecundity, and survival) and behavioral responses (*i.e.*, predator avoidance, habitat use and preference). Models then play a crucial role in scaling up such individual-level data, integrated across stressors, to understand population- and community-level properties relevant to management such as population persistence and multispecies harvest yields [15, 17].

Two empirical projects at UC Davis involving NRT-affiliated faculty provide individual-level data on multiple interacting impacts in managed species. These data will inform model development in NRT

courses, with connections to natural resource-dependent communities. First, co-PI Fangue is investigating the interactive effects of temperature, food availability, and swimming efficiency as a function of anthropogenic climate change and altered water flow regimes due to dams and water abstraction on anadromous green sturgeon (*Acipenser medirostris*). These studies assess physiological and behavioral metrics across developmental stages, including growth rate and survivorship. Scaling up such effects to understand the consequences for population persistence can inform the conservation management of green sturgeon. In addition, this project presents an opportunity to incorporate data-model integration methods into our existing partnership with the Yurok Indian Tribe in Klamath, CA. This multi-faceted partnership includes (a) the use of broodstock from the Tribal annual subsistence harvest for the provision of experimental organisms, (b) presentation of research findings annually to the Tribal Council, the Yurok fisheries biologists, and the community as a whole, and (c) ongoing discussions of best practices for the conservation and management of harvested species and the development of an outreach program to educate and train future Yurok Tribal biologists.

The second empirical project is spearheaded by participant Hill and features an industry-science partnership with The Cultured Abalone Farm to understand the interactive effects of ocean chemistry change (ocean acidification with increasing carbon dioxide) and hypoxia on red abalone (*Haliotis rufescens*). Red abalone are an iconic seafood species, historically collected by indigenous peoples, and commercial and recreational fisheries. Collapses in abalone populations caused by overfishing and disease [18] have required fisheries closures for many populations. Current UC Davis investigations include measuring the impacts environmental factors such as ocean chemistry, oxygen levels, temperature, diet, substrate, and location of origin on individual-level growth, mortality, shell size, tissue, and genome expression profiles. Scaling up such effects to understand the consequences for population dynamics is critical to inform management decisions such as closure areas, as well as locations and source populations to use for hatcheries.

d.2 **Fishing behavior: Scaling-up from satellite data to models of fishing fleets**. The bulk of research informing marine natural resource management lacks a detailed understanding of the range of economic, psychological, and cultural factors influencing individual fisherman as decision makers. Technological and scientific advances have the potential to fill this gap and enhance the ability to undertake evidence-based policy analysis across the human-natural system. For example, satellite-based tracking data from the vessel monitoring system (VMS) are now available on many fishing and shipping vessels around the world. VMS data provide information on ocean activities with a temporal and spatial resolution that dwarfs the historical data from trip logs and the mapping of activities to large statistical reporting grids (see Fig. 3 Panel A). The value of VMS data, however, has rarely been shown to managers beyond law enforcement (e.g., policing closed areas), despite the capacity to inform the assessment of spatial management policies such as marine protected areas (with exceptions; [19, 20]).

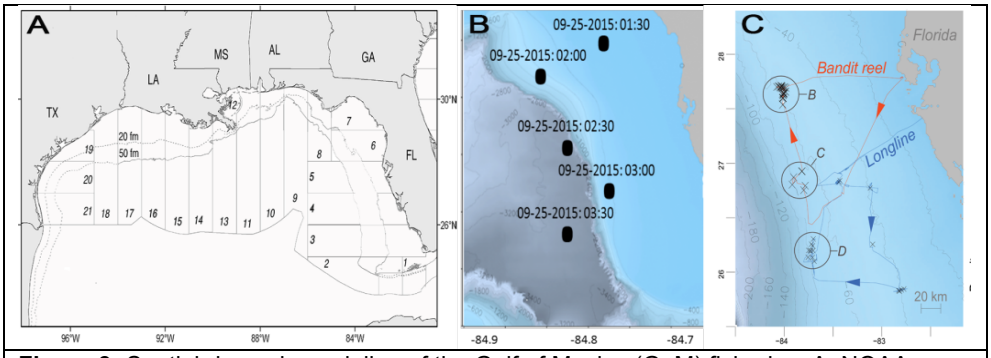


**Figure 3:** Spatial-dynamic modeling of the Gulf of Mexico (GoM) fisheries. A: NOAA statistical reporting areas for the GoM. B: Fishing boats equipped with a VMS unit automatically transmit present position (black dots) and timestamp at sub-hourly intervals. C: VMS tracks for two fishing vessels in the GoM (letters are potential fishing grounds).

The spatial and temporal richness of VMS data exemplifies the kind of "scaling-up and data-model integration" our NRT graduate training will prepare students for. We will use ongoing NSF-funded research (Sanchirico, PI) to train the students on how to combine unique forms of data derived from vessel monitoring systems, economic logbook, and ethnographic research to develop new types of decision-support tools for EBFM [21]. The basis of the research is understanding and predicting human spatial behavior in the face of changing ecological conditions. The research uses the Gulf of Mexico

(GoM) fisheries as a case study, specifically the red snapper and grouper-tilefish fisheries, because the GoM is a data-rich environment with which to test and extend models for evaluating decision-making.

Specifically, the objectives of the research are (1) to develop and validate machine learning techniques for processing VMS ping data (Fig. 3B) into fishing and non-fishing observations (Fig. 3C) by utilizing observer data as training data, and (2) to estimate and validate predictive models of spatial-dynamic decision-making of the fleet from the spatial-temporal data on individual vessels. The students will have access to the following data (in non-confidential form): (1) over 30 million hourly VMS position records from 2006-2015 with multiple observations on each fishing trip; (2) trip data on catches, revenue, vessel and skipper characteristics, and fishing costs; and (3) federal observer data that combine catch and VMS data on randomly selected trips. With these data, we will develop data sets for the students to investigate the potential biases from developing models of fishing behavior based on the traditional data aggregated to large statistical areas. This analysis will also highlight how these biases can affect the assessment of spatial management policies, such as the sea turtle closure areas implemented in the GoM to reduce bycatch of turtles in the longline fisheries, in both the design and evaluation stages. These exercises will provide insights into interpretation of models in data-poor settings (e.g., coarse spatial resolution) for decision-making.

d.3 **Marine protected areas: scaling up across space and time**. Given the increasing implementation of marine protected areas globally [22], a major challenge for marine science is the monitoring and adaptive management of MPAs, including changing boundaries or allowable uses. Adaptive management requires comparison of observed outcomes with expectations to determine whether MPAs are meeting anticipated goals [23]; however, near-term expectations for MPAs are inherently uncertain given environmental variability and poorly known life-history characteristics (e.g., dispersal scales [24]). California's MPA network, which arose from the Marine Life Protection Act of California (MLPA) in 1999, was implemented through a unique design process combining both stakeholder input and scientific analysis. UC Davis faculty have been, and continue to be, central players in developing the scientific underpinnings of the MPA network, from implementation to the newly-developing adaptive management plan (see, e.g., [25-28]).

We will use the California MPAs to train students in the integration of data and models to inform adaptive management [23]. Baseline (pre-establishment) monitoring of ecological and socioeconomic impacts of the network began in 2007. This large, multifaceted data set includes benthic habitat maps, biological and associated environmental data for diverse ecological communities, oceanographic data and socioeconomic data for fishing. Post-implementation monitoring continues, and will continue into the future. UC Davis efforts on MPA monitoring include collaboration with the California Department of Fish and Wildlife and the California Ocean Protection Council-–this includes three current post-doctoral scholars being jointly mentored between UC Davis faculty and CDFW scientists working on CA marine protected areas.

Specifically, we propose to train students to evaluate the effectiveness of the network of MPAs in the recovery of diverse ecosystems and fished populations. We will (1) analyze biological data for diverse communities inside and outside MPAs and changes in the communities since the establishment of the network; (2) analyze related environmental, oceanographic, fisheries landings data to evaluate the effect of environmental conditions and fishing pressure on communities across the network and over time; (3) analyze fishing logs to evaluate the effect of the establishment of the MPA network on changes in the behavior of the fishing fleet and socioeconomic indicators; and (4) model the impact of different management scenarios regulating fishing pressure on the recovery of commercially and recreationally important species inside and outside MPAs.

Engaging the trainees in MPA research provides the opportunity to train students in our four DESE cross-cutting themes. By definition, adaptive management is a prime example of data–model integration. Implementation of MPAs changes the uncertainty landscape in fisheries management [29]: no-take zones, for example, buffer against uncertainty associated with implementation of catch limits by protecting populations from overfishing, but no-take zones also introduce uncertainty due to poorly known larval dispersal patterns. Each MPA comprises a number of species with varying amounts of life history data available, and there will be variable amounts of monitoring data available at different locations, leading to data rich/data poor challenges. Finally, scaling up manifests in translating life-history data from individual MPAs to network-level population dynamics.

## e. **Broader Impacts**

The SOS:PSD NRT develops a novel paradigm to interdisciplinary training that moves the focus on policy to the front-end of the research enterprise, when questions are asked and hypotheses formed. Integrating the three new courses and an emphasis on hands-on exploration of what use-inspired research means through the use of **fieldtrips**, **internships**, and **basecamps** has the potential to revolutionize the dialogue between the scientific and policy community. Specifically, SOS:PSD has the potential to move the dialogue away from prescriptions that focus explicitly on improving communication skills of scientists to improving understanding of the complexity of policy design and assessment and how disciplinary research fits into the larger social-ecological landscape in which management interventions are undertaken. **All activities meet our long-term goal of training the next generation of quantitative marine scientists under a new paradigm that *begins with the decisions facing policy makers* to generate transdisciplinary use-inspired research questions**.

While we focus on marine resource management to demonstrate our approach, our training program is easily scalable and adaptable to any application of use-inspired research. At the same time, the SOS:PSD will leave a lasting imprint on the forthcoming PhD program in marine science and, as well as many environmental science and policy graduate programs at UC Davis. Additional legacies on graduate education at UC Davis will be the network of partners developed as part of SOS:PSD and the certificate program in marine resource management.

The SOS:PSD NRT builds on UC Davis' commitment to becoming a Hispanic serving institution (HSI) and on our strong record of broadening participation in the environmental sciences. NSF-funded environmental science IGERT programs at UC Davis that have recruited from similar graduate programs as this NRT have included >20% students from under-represented groups among their trainees; and we will increase the percentage over time with our innovative short and long-run approaches to recruitment. Specifically, our novel two-pronged approach to recruiting URMs will enhance, transform, and advance URM participation in marine science and we will forever change the research agenda by directly promoting the issues and perspectives of resource-dependent communities. The novel CMSI-COAST Scholars program includes Master’s students in our NRT, influences the research direction of the Scholars, increases their network and potential success in future endeavors (employment, graduate school), and forges new connections and strengthens existing ties between UC Davis and CSU faculty working in marine science and policy.

We will inform UC Davis and wider academic communities on best practices for transdisciplinary management problems by disseminating SOS:PSD curriculum and program evaluations. The assessment of our model by targeting participating students and faculty provides a comprehensive understanding of the challenges and opportunities for reshaping graduate education to meet the grand challenges in marine science. Besides serving the NRT trainees, our training elements are open to CSU students and other faculty and students on campus, thus expanding the impact of the training program.