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introduction

Developing and integrating enhancement strategies to improve and restore fisheries

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DEVELOPING AND INTEGRATING ENHANCEMENT STRATEGIES TO IMPROVE AND RESTORE FISHERIES

Proceedings of the 10th FSU–Mote International Symposium on Fisheries Ecology and 6th International Symposium on Stock Enhancement and Sea Ranching

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ABSTRACT.—Fisheries enhancements are management approaches involving the use of aquaculture and habitat technologies (in the broadest sense) to enhance or restore fisheries. The technologies most commonly used include hatchery rearing and release of aquatic animals and provision of artificial structures such as artificial reefs. Both are associated with distinct fields of knowledge and communities of practice. Recent calls to expand and broaden the role of aquaculture and habitat enhancements in marine conservation and an increasingly integrated view of living marine resource management have led to an aspirational broadening of concepts in this area. The 10th William R and Lenore Mote Symposium and 6th International Symposium on Stock Enhancement and Sea Ranching aimed to advance and integrate knowledge across enhancement technologies and practices. Substantial progress was noted in multiple technical areas such as understanding the potential and limitations for rearing organisms fit for release into the wild, and the design of artificial reefs to enhance local fish abundance. Crucial higher-level goals such as effectively enhancing or restoring fish abundance and fisheries at the stock level continue to receive insufficient attention across the enhancement sciences. Integration of enhancement strategies provides opportunities and challenges including a need to recognize, cross-discover, and engage other distinct areas of knowledge and communities of practice. A quick reference guide is provided to facilitate this process.

Fisheries enhancements are management approaches involving the use of aquaculture and habitat technologies (in the broadest sense) to enhance or restore fisheries in natural or altered ecosystems (Lorenzen 2014). Fisheries refer to the capture of aquatic organisms as a common-pool resource. The technologies used for enhancement purposes include hatchery rearing and release of aquatic animals (Bell et al. 2008b, Lorenzen et al. 2012), translocations of wild aquatic animals (Gardner et al.

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2015), and the provision of artificial habitat (Baine 2001), nutrition (Halldórsson et al. 2012), or predator control (Uki 2006) in natural settings. Releases of hatchery-reared aquatic animals and provision of artificial habitat in the form of artificial reefs are the most common forms of enhancements used in marine and coastal settings. Fisheries enhancements can be viewed as supply-side interventions in fisheries aimed at increasing production or access, in contrast to the harvest and other regulations that aim to achieve sustainable outcomes by limiting removals.

Despite similarities in high-level objectives and management issues, the scientific study of enhancements has proceeded largely separately for release of cultured animals and deployment of artificial reefs. For the former, the 1st William R and Lenore Mote Symposium on Fisheries Ecology and Enhancement held in 1996 (Travis et al. 1998) and the series of International Symposia on Stock Enhancement and Sea Ranching (ISSESR) held in Norway in 1997, Japan in 2002, the USA in 2006, China in 2011, Australia in 2015, and the USA again in 2019 have played an important role in shaping the study of marine fisheries enhancements into a coherent and rapidly advancing discipline. Proceedings of the symposia (Howell et al. 1999, Leber et al. 2004, Bell et al. 2008a, Lorenzen et al. 2013a, Taylor et al. 2017a, and the current issue) have been instrumental in reviewing and synthesizing scientific progress based on symposium presentations, exchange of ideas amongst delegates, and the wider literature, and in identifying directions for further research. For the latter, a series of over ten International Conferences on Artificial Reefs and Related Aquatic Habitats (CARAH) have played a similar role (Bortone 2015). The 10th William R and Lenore Mote Symposium and 6th ISSESR (*see* Fig. 1) aimed to advance and integrate knowledge across enhancement technologies and practices, including for the first time both release programs and artificial habitats. In keeping with the tradition of the ISSESR, this lead article aims to introduce the symposium contributions and also to review scientific progress and wider developments in the field since the last symposium (Taylor et al. 2017a,b). We start by discussing the renewed impetus of developing and integrating enhancement strategies before highlighting key recent developments in the science base of different enhancement approaches. We close by discussing potentials and limitations for development and greater integration of enhancement approaches.

New Impetus for Developing and Integrating Enhancement Strategies

Owing in no small part to the symposia series mentioned above and the communities of science and practice they have fostered, enhancement science has made great strides over the past 25 years. In their synthesis of the 4th ISSESR, Lorenzen et al. (2013b) argued that the science base for aquaculture-based fisheries enhancements had reached a point where enhancement systems can be effectively designed and their potential contribution to fisheries management goals quantitatively evaluated, thus effectively making such approaches available to coastal fisheries management. They also noted contextual factors that would likely lead to greater calls for such approaches to be considered, including global environmental change impacts on coastal ecosystems and fisheries, expansion of captive breeding and domestication of new marine species, and adoption of rights-based fisheries governance systems that can provide incentives for active approaches to maintaining fisheries yields and ecosystem services. Since then, global change impacts on coastal ecosystems have rapidly

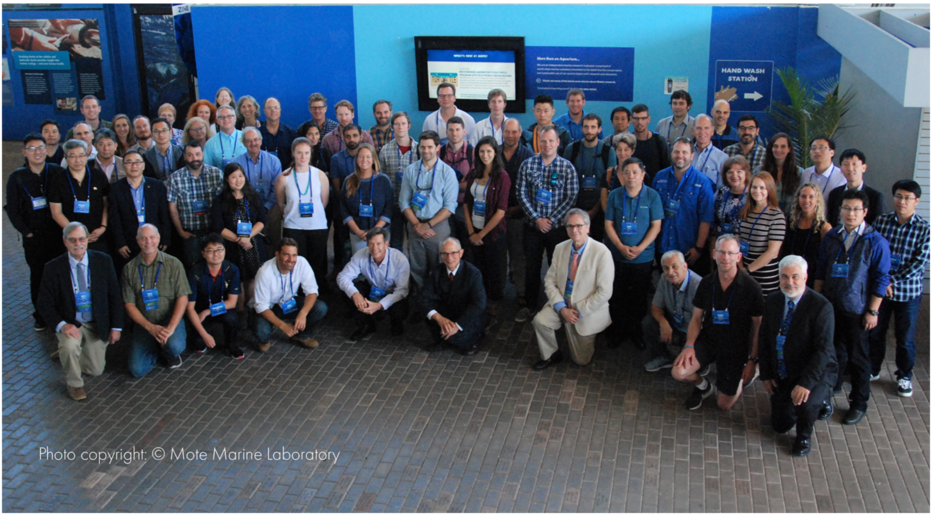

Figure 1. Delegates at the 10th William R and Lenore Mote International Symposium and 6th International Symposium on Stock Enhancement and Sea Ranching held at Mote Marine Laboratory, Sarasota, Florida, USA, November 10–14, 2019 (© Mote Marine Laboratory).

intensified (Halpern et al. 2019, Suryan et al. 2021) and aquaculture has continued to grow worldwide (Garlock et al. 2020). Calls to expand and broaden the role of aquaculture in marine conservation have followed, with emphasis on both the potential for aquaculture to produce food with a comparatively low climate footprint and to help restore marine populations (Froehlich et al. 2017, Clavelle et al. 2019). This represents a substantial shift in attitudes particularly for North America, where marine aquaculture has traditionally been viewed more as a conservation threat (Knapp and Rubino 2016). It also signifies a shift towards an increasingly integrated view to living marine resource management that has long been prevalent in Asia but less so in the western world where fisheries and aquaculture are seen as dichotomous (*see also* Klinger et al. 2013, Lorenzen 2014). At the same time, government policies in China (the world's largest fisheries and aquaculture producer) have place renewed emphasis on the development of marine ranching as an overarching concept for coastal resource management that closely integrates fisheries, aquaculture, habitat, and other marine resource uses including tourism (Zhou et al. 2019, Qin et al. 2020). It is therefore timely to examine how the knowledge base of the fisheries enhancement sciences and the systematic planning processes that have been developed—e.g., for stock enhancement programs (Blankenship and Leber 1995, Lorenzen et al. 2010)—can be expanded and integrated to effectively address the new and broadening opportunities and challenges outlined above.

Science Advances and the Development of Enhancement Strategies

Aquaculture and Genetic Management.—Efficient aquaculture production of seed organisms that perform well under natural conditions is a prerequisite for effective and economically viable enhancement or restoration. Unfortunately, cultured organisms often perform poorly in the wild due to developmental and genetic effects of culture on many aspects of their biology (Lorenzen et al. 2012). Näslund (2021) provides a major synthesis of the current state-of-knowledge of interventions aimed at ameliorating cognitive and behavioral deficiencies in aquatic animals reared for stocking. The paper aims to provide a foundation to assist in the development of future questions, hypotheses, and experiments to eventually improve the postrelease performance of these animals. A great deal of research and practical effort has been invested in this area over the past twenty years, but substantial gains in postrelease performance of organisms reared in aquaculture have materialized only occasionally and under quite specific circumstances. Early optimism in that respect has not been borne out in practice (Brown and Day 2002). Domestication effects can manifest themselves in many different aspects of the organisms' biology. Caldentey et al. (2021) show that prey capture kinematics differ between naïve hatchery juvenile snook and wild conspecifics, with hatchery fish making fewer attempts to feed, longer delays in the time to strike, exhibiting higher strike velocities, and engulfing prey earlier in the gape cycle, resulting in overall lower feeding success compared to wild fish. However, feeding success improved with repeated live prey feeding experiences. Silbernagel et al. (2021) show how a semiquantitative assessment and control program can be developed to document and reduce the incidence of abnormal physical attributes in reared fish prior to their release. This program has proven to be useful for identifying malformations and minimizing the release of affected cultured marine fish. Grant et al. (2017) synthesized genetic considerations in a "responsible genetic approach to stock restoration, sea ranching and stock enhancement."

Release Strategies and Postrelease Ecology.—Release strategies (habitat, size, season, etc.) greatly influence immediate postrelease survival and ecological interactions of hatchery fish in the wild and have long been a focus of fisheries enhancement research. However, the ability to monitor the performance of organisms past release is often limited. Five papers in the current proceedings demonstrate innovative approaches to postrelease monitoring and the utility of release experiments to inform management. Schloesser et al. (2021) developed an approach to assess short-term apparent survival of hatchery-reared fish stocked into open estuarine systems, using an array of pit tag antennae. Resighting histories were best explained by short-term differences in apparent survival among the first few weeks and long-term patterns in detectability driven by residency behaviors. Further application of this approach will help refine optimal release locations, times, and procedures, promote adaptive management of enhancement programs, and maximize the benefits of strategic, science-based stocking on receiving populations. Taylor et al. (2021) demonstrate application of sibship analysis to retrospectively infer the origin of fish stocked in estuaries, when other means of identification were not available. The results highlight that sibship analysis may be useful for retrospective genetic evaluation of stocked estuaries. Becker et al. (2021) used a pilot stocking program to evaluate if estuarine artificial reefs are suitable release habitat for juvenile yellowtail kingfish, and monitored their dispersal patterns using acoustic telemetry and a tag-recapture program. Stocked yellowtail kingfish likely dispersed rapidly from release locations which is consistent with their pelagic life history, but there was little interaction between stocked fish and two large coastal artificial reefs. Gorospe et al. (2021) showed the potential for experimental approaches to explore ecological interactions following release, particularly for relatively sessile benthic invertebrates. Translocation is a traditional management practice in certain shellfish fisheries (Spencer 2002) and has been implemented experimentally in others (Gardner et al. 2015). Tomiyama and Sato (2021) show how a rigorous experimental evaluation of the practice can help identify promising strategies for increasing clam production in a Japanese estuary.

Population Dynamics and Quantitative Assessment of Stock Enhancements.—Quantitative research on the population dynamics of aquaculture-based enhancement and restoration measures is central to assessing their contribution to fisheries management goals (Lorenzen 2005). A key consideration is when in the life cycle mortality is strongly density-dependent, since stocking before or during this phase is likely to incur an immediate, partial compensatory reduction in the abundance of naturally recruiting juveniles and reduce the overall contribution of released hatchery fish. A meta-analysis by Lorenzen and Camp (2019) showed that in fish populations, density-dependence in survival is strongest when juveniles are smaller than 10% of the species' maximum body length and is not evident at all above 20% of maximum length. This provides practical guidance for the parameterization of enhancement models and the design of release programs when, as is commonly the case, population-specific information on the occurrence of density-dependence in the lifecycle is unavailable. A modeling study by Johnston et al. (2018) explored how outcomes of stock enhancements and harvest regulations are influenced by a broad range of ecological processes. Several long-term studies in population dynamics of enhanced fisheries have been reported recently. Amoroso et al. (2017) showed that pink salmon enhancements in Alaska have been successful at increasing overall harvest, while reducing the returns of naturally recruited stock components. Long-term monitoring and assessment of a restocking program for the estuarine sparid *Acanthopagrus butcheri* in the Blackwood River Estuary of south-western Australia revealed that the releases had a significant, positive effect on recruitment and population abundance (Cottingham et al. 2020). Natural recruitment in this system is very episodic and releases were carried out while natural recruitment was low. An evaluation of the long-running California white seabass enhancement program concluded that stocking had a very small additive effect without adversely affecting natural recruitment. However, the overall magnitude of the additive effect was miniscule due to very high postrelease mortality of hatchery fish, and cost of releases substantially exceeded the economic benefit generated (California Sea Grant 2017). Stoner (2019) reviewed 40 years of work aimed at rebuilding conch populations in the Caribbean and concluded that survival of stocked conch juveniles was consistently insufficient to achieve rebuilding goals, and highlighted the need to prioritize conservation of natural conch populations where possible over application of aquaculture-based rebuilding strategies.

Artificial Reefs.—Research on artificial reefs has focused predominantly on the structure of populations and communities directly associated with artificial habitats and on the influence of reef design and materials (Lima et al. 2019). Conversely, quantitative research on the impact of artificial reefs on fish and fisheries is rare, but sorely needed (Becker et al. 2018). That is particularly true for studies at the scale of whole stocks or management units. Two articles in the current volume provide important advances. Blount et al. (2021) propose guiding principles for the development of artificial reef programs from an ecological perspective, building on a review of the literature and emphasizing the potential for need for systematic reviews to support implementation of principles. Ramm et al. (2021) assembled a database of artificial reefs as a basis for systematic reviews and meta-analyses. They further presented a standardized protocol for describing artificial reefs in published studies and urged authors to include the relevant data to allow future comparisons to enhance our understanding and evaluation of these structures.

Enhancement Systems.—System-level analyses are key to fully evaluating the potential of enhancements vis-à-vis other fisheries management measures (Lorenzen et al. 2010). A recent, worldwide review of marine stock enhancements by Kitada (2018) provides important insights. Even though a plethora of release experiments involving over 180 species have been reported in the scientific literature, very few studies evaluated impacts on fishery production, let alone economic outcomes. Often, studies showed low contributions of stocked vs wild recruits, compensatory density-dependence affecting wild and stocked organisms, and substantial gene flow from hatcheries, though fitness reduction in stocked populations has not been reported. Most reported enhancement cases were economically unprofitable or unevaluated. Also noteworthy is a wide ranging, integrative review of Australian stock enhancement programs in freshwater systems by Hunt and Jones (2018), which reiterated the need for quantitative goals and improved assessments of social and economic outcomes from releases. In the present volume, Cárcamo et al. (2021) review restocking, stock enhancement, and translocation efforts aimed at supporting artisanal fisheries in Chile. Chile offers governance conditions uniquely favorable to the development of enhancements because artisanal fisheries are managed through a system of inshore spatial use rights. Marine stocking mainly occurred within the context of the artisanal spatial management framework, and over 60% of the projects reviewed involved the translocation of wild individuals rather than release of hatchery-reared seed. Only 6% of projects examined reported positive results that could be linked to releases, and none reported the use of tagging or analysis of costs or benefits. This illustrates again that even where governance arrangements are conducive and science organizations are involved, many enhancement initiatives continue to be pursued without drawing on the systematic planning and development processes and tools available.

Developing and Integrating Enhancement Strategies: Opportunities and Challenges

Congruence of High-Level Objectives and Issues, Opportunities for Cross-Fertilization at the Technical Level.—Different forms of fisheries enhancements have high-level objectives and management issues in common but differ in more specific technical considerations. For instance, both stock enhancement and artificial reef programs may aim to increase fish availability to recreational anglers and may need to manage exploitation of the enhanced fisheries to prevent negative sustainability feedbacks from fishing effort responses. Depending on the situation, employment of different enhancement approaches or combinations of approaches may improve the likelihood that enhancement or restoration goals will be achieved. It is therefore desirable to move toward developing a common framework for integrating enhancement approaches. At the more detailed technical level, there are substantial opportunities for cross-fertilization (Lorenzen 2014). For example, a population dynamics and genetics model developed to support the hatchery reform process in the Pacific Northwest of the USA (Mobrand et al. 2005, Mobrand, Jones, and Stokes 2006) has been modified to serve as a tool for genetic risk assessment of escapes from offshore aquaculture (Volk et al. 2015). Likewise, artificial reef science has provided a framework for understanding and managing the ecological and fisheries impacts of attraction of wild fish to offshore cages (Sanchez-Jerez et al. 2011). To facilitate such cross-fertilization and cross-discovery of knowledge, we draw attention to the many different terminologies and communities of practice involved in fisheries enhancement and related research. To this end we provide a quick reference guide to fisheries enhancement-associated and equivalent terms in Table 1.

Reinvigorating and Unifying the Fisheries Sciences.—Scholars of both stock enhancement and artificial reefs have noted how fisheries enhancements force scientists to address many fundamental questions in the fisheries sciences and provide unique opportunities for experimental research on management-relevant scales (e.g., Seaman et al. 2011, Lorenzen 2014). This potential is also evident from various recent contributions described above, but in general remains under-utilized.

Loss of Knowledge due to Shifting Concepts, Terminologies, and Communities of Practice.—While there is great potential for integration and cross-fertilization among the different areas of enhancement and related sciences, there is also a potential for loss of established knowledge due to shifting concepts, terminologies, and communities of practice. For example, the broadened concepts of conservation aquaculture and marine ranching are aspirational and suggest the existence of great opportunity and a need for innovative research. At the same time, many if not most of the constituent practices such as stock enhancement/restocking or the placement of artificial reefs have been extensively researched under different terms and by different communities of practice. Most importantly, rigorous research has demonstrated strong limits to the effectiveness of these approaches under most conditions. Therefore, loss of this knowledge is not neutral in character but is likely to lead to unduly optimistic expectations of the potential benefits of such approaches. Again, we encourage scientists and practitioners to look out for different terminologies and communities of practice that can either inform their own work or suggest new applications for it (Table 1).

Developing and Reforming Enhancements: the Challenge of Policy and Practice.—Despite the availability of science, assessment tools, and planning processes, in policy and practice the adoption of such rigorous approaches to the development of new (and reform of existing) enhancements has been slow. As discussed above, a large proportion of marine stock enhancements have not been sufficiently evaluated and among those that have been, a majority were shown to be ineffective and/or not economically viable. This illustrates the importance of continuing and expanding collaborative efforts with stakeholders to assess and reform enhancements (Mobrand et al. 2005, Lorenzen et al. 2010, Fujitani et al. 2017). Effective stakeholder engagement is a crucial element of any such initiative, and several recent studies chart new avenues in this respect. Fujitani et al. (2017) highlighted the potential for participatory adaptive management to lead to effective learning among stakeholders improved management outcomes for fish stocking programs. Harrison et al.

Table 1. Quick reference guide to fisheries enhancement: related and equivalent terms. This table is intended to facilitate cross-discovery of relevant literature and communities of practice.

Term	Meaning and Equivalent Terms
Artificial habitats, structures, and reefs [c, e]	Placement of artificial habitats including artificial reefs in natural ecosystems to enhance or restore fish populations or fisheries. One approach to fisheries enhancement and a key component of marine ranching (China).
Aquaculture-based fisheries enhancement [j]	All forms of fisheries enhancements involving aquaculture technologies, including conservation aquaculture (narrow sense), culture-based fisheries, restocking, sea ranching, and stock enhancements.
Aquaculture-fisheries interactions [f, g, k]	Include aquaculture-based fisheries enhancements as well as other interactions to which the knowledge base of fisheries enhancement science is broadly applicable (e.g., ecological and evolutionary impacts of escaped farmed fish, aggregation of wild fish around cages).
Captive breeding [a, k]	Maintenance of populations in captivity, usually over multiple generations, for the purpose of ex situ conservation and eventual reintroduction.
Conservation aquaculture (broad sense) [g]	Use of aquaculture to further conservation goals. Includes but is not limited to any form of fisheries enhancement.
Conservation aquaculture (narrow sense) [b, p]	Time-limited releases of cultured fish aimed at rebuilding depleted populations more quickly than would be achieved by natural recovery. Broadly synonymous with restocking and restoration aquaculture.
Culture-based fisheries [j, k]	Release of cultured organisms that do not recruit naturally in the target system, aimed at increasing fish production and/or abundance. Term used in inland waters, equivalent to sea ranching.
Extensive aquaculture or mariculture [p]	Aquaculture that utilizes natural biological productivity as a food supply. May incorporate certain types of fisheries enhancements such as artificial habitats, culture-based fisheries, or sea ranching.
Fisheries enhancement [j]	Use of aquaculture and/or and habitat technologies to enhance or restore fisheries.
Hatchery program [l]	Synonymous with all forms of aquaculture-based fisheries enhancements, i.e., culture-based fisheries, restocking, sea ranching, stock enhancement, supplementation, restoration aquaculture, reintroduction.
Marine ranching (China) [n, r]	Broad term incorporating all forms of fisheries enhancements, with emphasis on deploying artificial habitat.
Propagation [o]	Synonymous with all forms of aquaculture-based fisheries enhancements, emphasizes the culture operation. Traditional term.
Reintroduction [k]	Temporary releases of cultured or captured fish with the aim of reestablishing a locally extinct population.
Restocking [d, k]	Time-limited releases of cultured fish, aimed at rebuilding depleted populations more quickly than would be achieved by natural recovery. Broadly synonymous with conservation aquaculture and restoration aquaculture.
Restoration aquaculture [m]	Use of cultured animals to help rebuild natural populations from low abundance. Broadly synonymous with restocking and (narrow sense) conservation aquaculture.
Sea ranching [d, j, k]	Release of cultured organisms that do not recruit naturally in the target system, aimed at increasing fish production and/or abundance. Term used for marine or anadromous species, equivalent to culture-based fisheries in inland waters.
Stock enhancement [d, j, k]	Continued release of cultured fish into a self-recruiting wild population with the aim of sustaining and improving fisheries in the face of intensive exploitation and/or habitat degradation.
Supplementation [k, j]	Supplementation is defined here as the release of cultured fish into very small and declining populations with the aim of reducing extinction risk and conserving genetic diversity.
Translocation [h, i]	Deliberate movement of organisms from one site for release in another, carried out for conservation or production purposes. Involves at least temporary holding in aquaculture facilities and overlaps with many forms of aquaculture-based enhancement, e.g., culture-based fisheries, restocking, stock enhancement.

[a] Anders 1998, [b] Andrews and Kaufman 1994, [c] Baine 2001, [d] Bell et al. 2008b, [e] Bortone 2015, [f] Clavelle et al. 2019, [g] Froehlich et al. 2017, [h] Gardner et al. 2015, [i] IUCN/SSC 2013, [j] Lorenzen 2014, [k] Lorenzen et al. 2012, [l] Naish et al. 2007, [m] Patterson 2019, [n] Quin et al. 2020, [o] Shelbourne 1964, [p] Troadec 1991, [q] Wasson et al. 2020, [r] Zhou et al 2019

(2018) examined the psychological, social, and conservation benefits that stakeholders derive from hatchery programs and discussed how inclusion of these benefits in management considerations may lessen conflict over use of aquaculture-based enhancements. Obregón et al. (2020) demonstrated a new two-phase approach to eliciting and measuring beliefs about fish stocking programs from stakeholders. In the development of new enhancements, it is vital to conduct prognostic evaluations prior to major investments in enhancements, because once those investments have been made, enhancements have proved very difficult to reform. The updated responsible approach to marine stock enhancement (Lorenzen et al. 2010) strongly urges planners to conduct such prognostic evaluations, and relevant modeling tools are available for stock enhancements (Lorenzen 2005, Mobrand, Jones, and Stokes 2006, Garlock et al. 2017). On the other hand, tools to support the prognostic modelling of regional impacts of artificial reef deployments are less readily available but may be on the horizon (e.g., Roa-Ureta et al. 2019). It is highly likely that the same considerations will remain relevant as broader and more integrated enhancement concepts emerge and are put into practice.

Symposium Details and Awards

The 10th William R and Lenore Mote Symposium and 6th International Symposium on Stock Enhancement and Sea Ranching was held at the Mote Marine Laboratory in Sarasota, Florida, 10–14 November, 2019. The symposium was sponsored by the Florida State University William R and Lenore Mote Endowment, Mote Marine Laboratory, and NOAA Fisheries—Office of Aquaculture. The steering committee for the symposium included (in addition to ourselves) L Barbieri, M Rust, L Blankenship, K Main, C Peterson, M Denson, and M Drawbridge. The award for the best paper by a young investigator went to A Pilnick, University of Florida, Gainesville, Florida, for his paper (coauthored with J Patterson and K O'Neil) entitled "Developing intensive aquaculture of the long-spined sea urchin *Diadema antillarum* as a tool for coral reef restoration". The award for the best poster from a young investigator went to P Chauvaud, Laboratoire des Sciences de l'Environnement Marin, Université de Bretagne Occidentale, Brest, France for his poster (coauthored with S Huchette and S Roussel) entitled "First step in the preparation of stock-enhancement for the European abalone (*Haliotis tuberculata*) in Brittany, France."

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