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The mobilization of science and technology fisheries innovations towards an ecosystem approach to fisheries management in the Coral Triangle and Southeast Asia

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ABSTRACT

Several regional fisheries and marine conservation organizations in the Coral Triangle (CT) and Southeast Asia have indicated their support for an ecosystem approach to fisheries management (EAFM). It is also likely that science and technology (S&T) innovations will play a role in the region for the purposes of filling gaps in fisheries data, enhancing the coordination of fisheries management efforts, and implementing and operationalizing an EAFM. Here, we outline the methodology and results of an expert-opinion survey designed to elucidate and prioritize the implementation of these S&T innovations. As a first step and case study, the survey presented here was conducted on U.S. government experts. The U.S. market is one of the world's largest importers of seafood, and therefore, in the framework of this study, is considered to be a stakeholder in the seafood supply chain that originates in the CT and Southeast Asia region. Results are discussed in terms of the data needs and principles of an EAFM, as well as current trends and contexts of the CT and Southeast Asia region. Next steps and recommendations are also provided on how S&T innovations can be implemented to enhance the cooperation and coordination of regional marine resource management efforts.

1. Introduction

The Coral Triangle and Southeast Asia region is composed of a complex myriad of interwoven environmental, social, economic, and political contexts [14]. In order to sustainably manage the marine fisheries and biodiversity of this dynamic region, decision-makers must balance the multitude of objectives that arise from its diverse resource users. Several regional organizations, such as the Coral Triangle Initiative (CTI), Southeast Asian Fisheries Development Center (SEAFDEC), and Asia Pacific Fisheries Commission (APFIC), have recognized the ecosystem approach to fisheries management (EAFM) as a more inclusive and holistic approach to fisheries management [32]. By being inclusive of all stakeholders that benefit from and/or potentially impact fisheries and their supporting ecosystems, seeking their input during the earliest planning stages, and adapting management actions based on continued monitoring and reassessment, an EAFM is considered the preferred option and best practice for ensuring the long-term sustainability of fisheries and the marine ecosystem services provided to society [12,13].

Management plans in the region are already moving forward in the implementation of an EAFM. For example, some organizations, such as SEAFDEC have already begun the dissemination of EAFM trainings throughout the region [32]. Furthermore, the countries that border the Sulu Sulawesi Sea Large Marine Ecosystem - Indonesia, Malaysia, and the Philippines – have already developed a strategic plan that includes ecosystem-level priorities and indicators [37]. While progress has been made, in practice, national government agencies around the globe are still determining how

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best to implement such a multi-sector (across agencies), multi-scale (matched to both local and national management processes) initiative [30].

One of the challenges of moving towards an EAFM is that this approach explicitly broadens the scope of fisheries data collection beyond target species and into the realm of whole ecosystems, taking into consideration the biological, physical, and human components of the system that influence the productivity and sustainability of fisheries and the well-being of people. Science and technology (S&T) innovations, if mobilized properly, have the ability to optimize integrated data collections and disseminate high quality scientific information in a timely manner, thus enhancing the salience, credibility, and legitimacy of this information [3] and allowing for effective implementation of an EAFM.

For the Coral Triangle / Association of Southeast Asian Nations (CT/ASEAN) region in particular, S&T innovations have the potential to spur the region beyond simply embracing EAFM policy, and actually operationalizing one. For example, major data gaps exist for the region, especially in terms of the species composition of its fisheries catch [10]. Demographic information on the fishers themselves is also largely missing; small-scale (i.e., artisanal or subsistence) fishers are not currently represented by any regional organization, and thus engagement with this sector has been limited [31]. This is particularly worrying given the large and growing contribution of this sector to fisheries production in the region [25].

Furthermore, there is international interest in addressing illegal, unreported, and unregulated (IUU) fishing in the region. Recent evidence has suggested that a significant portion of wild-caught seafood imported into the U.S. (20-32% by weight, or over $1 billion worth) is made of illegal or unreported catches [34]. Therefore, as one of the world's largest importers of seafood, the U.S. market, in the framework of this study, is considered to be a stakeholder in the seafood supply chain that originates in the CT/ASEAN region. U.S. interest in the region is evidenced by their 5-year investment of over $40 million of technical and financial assistance to the Coral Triangle countries as part of the U.S. Coral Triangle Initiative Support Program [6]. More recently, this initiative has been expanded into the Oceans and Fisheries Partnership, focused on combatting IUU and mobilizing S&T innovations to enhance communication and seafood catch traceability in the region. Another international initiative, the recently signed Trans-Pacific Partnership trade agreement, includes the U.S. as well as several countries in the region as signatories and contains provisions to take collective action against overfishing and IUU.

Coordinating enforcement efforts in the CT/ASEAN region, however, is complicated by the numerous countries, governing systems, ethnic and socio-economic groups, and industries that have the potential to clash over fishing rights and access [14,33]. S&T innovations that collect, integrate, and share information, may provide the credibility and validation needed to bring diverse stakeholders to the table. On the other hand, the implementation of S&T can be highly technical, jargon-laden, and inaccessible, and thus runs the risk of alienating non-scientific stakeholders. When implemented under the guiding principles of an EAFM, however, S&T innovations have the potential to not only help with data collection, surveillance, and enforcement in the region, but also with reaching out to groups that have largely been left out of the fisheries management process.

This paper outlines: (i) a survey that was developed to begin discussions on how S&T innovations could be used for sustainably managing trans-boundary (i.e., trans-national) fisheries in the CT/ASEAN region as well as the overall seafood supply chain leading into the U.S. market and (ii) the results of a pilot case study that focused on one set of stakeholders – i.e., the opinions of experts from the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA), as well as several agencies within the U.S. Department of Interior (DOI). The results of the case study survey are discussed in terms of the data needs and principles of an EAFM, as well as current trends and contexts of the CT/ASEAN region. Due to the limited scope of this case study, however, the results presented here cannot be generalized to the needs and opinions of the CT/ASEAN region. The method outlined here should be conducted across multiple stakeholder groups, including fisheries scientists, managers, and fishermen throughout the CT/ASEAN region to spur discussions of how fisheries S&T could be coordinated and implemented on an international level.

2. The link between an ecosystem approach to fisheries management and science and technology innovations

A point of clarification should be made here to distinguish EAFM from EBFM, or ecosystem-based fisheries management. The U.S. NOAA uses distinct biological hierarchical levels to differentiate between EAFM and EBFM [22], with EAFM focused on single-species stocks and EBFM focused on multiple species, but with both models aimed at integrating wider ecosystem components. Given its international implications, this article instead employs the United Nations Food and Agriculture Organization's (FAO) definition of an EAFM [12]. While the FAO definition does not differentiate between single and multiple-species management, its emphasis on balancing ecological well-being and human well-being through good governance has already been adopted by several regional organizations in Southeast Asia and the Coral Triangle. Despite these nuanced definitions, it is important to shelter the implementation of an EAFM/EBFM from being "crippled with linguistic uncertainty" [28]. Thus, this report uses the term EAFM throughout, while recognizing that the common goal of both the FAO's EAFM and the U.S. NOAA's EBFM/EAFM is to move beyond single-species traditional fisheries management and that, in reality, there are aspects of both approaches that should be incorporated into the next generation of fisheries management plans [21].

It is also important to emphasize that while the data requirements for operationalizing an EAFM are broader and more comprehensive [16], they are not insurmountable. In fact, it is a myth that an EAFM can only be implemented in regions with a plethora of data [28]. Dispelling this myth is particularly important for implementing an EAFM in the CT/ASEAN region where data on fisheries and other physical and social components of the ecosystem may not be readily available. EAFMs can and should be implemented in data-poor situations, for example, by using traditional local knowledge and best available natural history information to define cautious policies at first (i.e., the precautionary principle), but with the flexibility to adapt these policies as new information becomes available [29]. In fact, fisheries managers from data poor regions are already developing ecosystem indicators and implementing a range of decision frameworks from qualitative to fully analytical [23,39].

3. Methodology

The survey's framework and questionnaire were developed with the guidance of S&T experts from throughout NOAA and DOI (i.e., the S&T core group). Among the core group's first task was to create a list of S&T innovations that could: (1) be implemented in the CT/ASEAN region in the next 5 years, and (2) address trans-boundary fisheries in the region. Using these criteria, a total of 21 S&T innovations were identified in our final list (Table 1), falling into three categories: (i) field-based or remote data acquisition, (ii)

Table 1
List of 21 science and technology innovations used in our survey.

Field or remote-based data acquisition
Active acoustics
Automatic Identification System (AIS)
Autonomous underwater vehicles (AUV)
Drifting fish-attracting devices (DFADs)
Electronic monitoring
Electronic reporting
Mobile phone and crowd-sourcing apps
Oceanographic remote-sensing data
Over-the-horizon radar
Passive acoustics
Unmanned Aerial Vehicles (UAVs)
Vessel light detection using satellites
Vessel Monitoring System (VMS)
Laboratory-based data acquisition
Forensic labs
Next generation sequencing technologies
Population genetic analyses
Seafood safety and quality testing
Data analysis methods
Climate and ocean change predictions
Integrated ecosystem and socio-economic models
Seascape ecology
Stock assessment analyses

laboratory-based data acquisition, and (iii) data analysis.

Next, for each S&T innovation, the S&T core group developed an analysis of strengths, weaknesses, opportunities, and threats (SWOT). Here, strengths and weaknesses were defined as characteristics of the technology that place it at an advantage or disadvantage, respectively, over similar technologies. On the other hand, opportunities and threats were defined as characteristics of the required infrastructure (e.g., political, financial, human resources, etc.) that could potentially advance or hinder, respectively, the successful implementation of this technology. The SWOT analyses for each of the 21 S&T innovations accompanied the survey as an information resource, thus ensuring that all survey participants had at least a basic understanding of each S&T's capabilities before answering the survey questions.

The survey's overall framework was based on the seafood supply chain. The seafood supply chain was used to classify fisheries management information needs into five categories (Fig. 1): pre-catch, point-of-catch, point-of-processing or packaging, point-of-purchase or consumption, and integration of the seafood supply chain. The survey asked participants to select the one S&T innovation which, if implemented in the next 5 years, will have the greatest impact on the information needs of trans-boundary marine fisheries in the CT/ASEAN region. This was asked separately for each of the five seafood supply chain categories. In addition to selecting the most effective S&T innovation for improving management at each point along the seafood supply chain, participants were asked to explain the main advantage and main barrier to implementing each of the S&T innovations they selected.

Although the study would have clearly benefited from including fisheries managers in the CT/ASEAN region as part of the survey, the scale of the project was limited for practical reasons to the voluntary input of U.S. government employees working in a fisheries and marine conservation context. A request for survey participants was sent out by NOAA's International Affairs Council to all six of NOAA's fisheries science centers, looking for experts with the following specialized skills: (i) technical or managerial experience on several of the S&T innovations included in the survey, and/or (ii) working experience in international capacity building for fisheries management. Thus, despite the lack of international input in the current study, the depth and breadth of expertise among the survey participants still lends some validity to these results.

4. Results

The survey collected input from a total of 62 participants (53 from NOAA and 9 from DOI). For pre-catch management information needs, they gave the most support to stock assessment analyses (Fig. 2A). For the remaining four management information categories, electronic reporting was among the top three most supported S&T innovations (Fig. 2B-E). Furthermore, if the data are categorized into experts who self-identified as having experience and/or knowledge of fisheries issues specific to the region vs. those with little to no experience/knowledge, we see no differences in the S&T innovations that are highlighted by each group (Fig. 2A-E). This further suggests that the advice derived from the survey is robust, despite having no input from fisheries scientists and managers from the CT/ASEAN region. Nevertheless, a follow-up survey should eventually be conducted with fisheries experts from the CT/ASEAN region and compared to the results reported here.

This paper also highlights results at the point-of-catch category as these S&T innovations could potentially help address the issue of IUU fishing in the region (Fig. 1), an issue that is particular important to the U.S. as a major importer of seafood originating from the region. For the point-of-catch category, the top two S&T innovations selected by survey participants were electronic monitoring and vessel monitoring systems (VMS; Fig. 2B). Based on survey responses regarding the main barriers to S&T implementation, however, it was revealed that the cost of implementing and maintaining these S&T would pose a significant financial challenge. Furthermore, these S&Ts have already received considerable attention in the literature [15,36,46,5]. Indeed, both of these tools are gaining traction worldwide, particularly among regional fisheries management organizations attempting to set up monitoring, control, and surveillance (MCS) systems on the high seas. For the CT/ASEAN region, we believe these systems will continue to hold promise, but primarily for large-scale industrial fishing operations. This paper, however, highlights two alternative S&T innovations for the point-of-catch category: (i) mobile phone and crowd sourcing apps, and (ii) vessel light detection using satellites. Each of these S&T innovations received moderate support in our survey. Furthermore, based on survey participants' short answer responses, these are not considered to be particularly cost-prohibited. More importantly, these S&T innovations are already being implemented in the region and demonstrating their utility.

Finally, the SWOT analyses for the four S&T innovations – stock assessment analyses, electronic reporting, mobile phone and crowd sourcing apps, and vessel light detection using satellites – discussed in this article are provided in the Appendix.

5. Discussion

5.1. Stock assessments analyses under an EAFM

There was overwhelming support among the survey participants for stock assessments as an S&T solution for pre-catch fisheries management needs (Fig. 2A). Fisheries management in the U.S. has a long history of reliance on stock assessment output as the basis for setting catch regulations, determining stock status, and rebuilding overfished stocks [44]. Yet, the strong support in the survey results for stock assessments was surprising because these analyses do not traditionally address many of the other pre-catch fisheries management needs as described in Fig. 1. For example, is the biological (i.e., species or genetic) diversity preserved? How will the fishery be impacted in the future by climate change? Answering these questions requires that information beyond traditional single-species stock assessment outputs also be included in management decision-making. In fact, other S&T

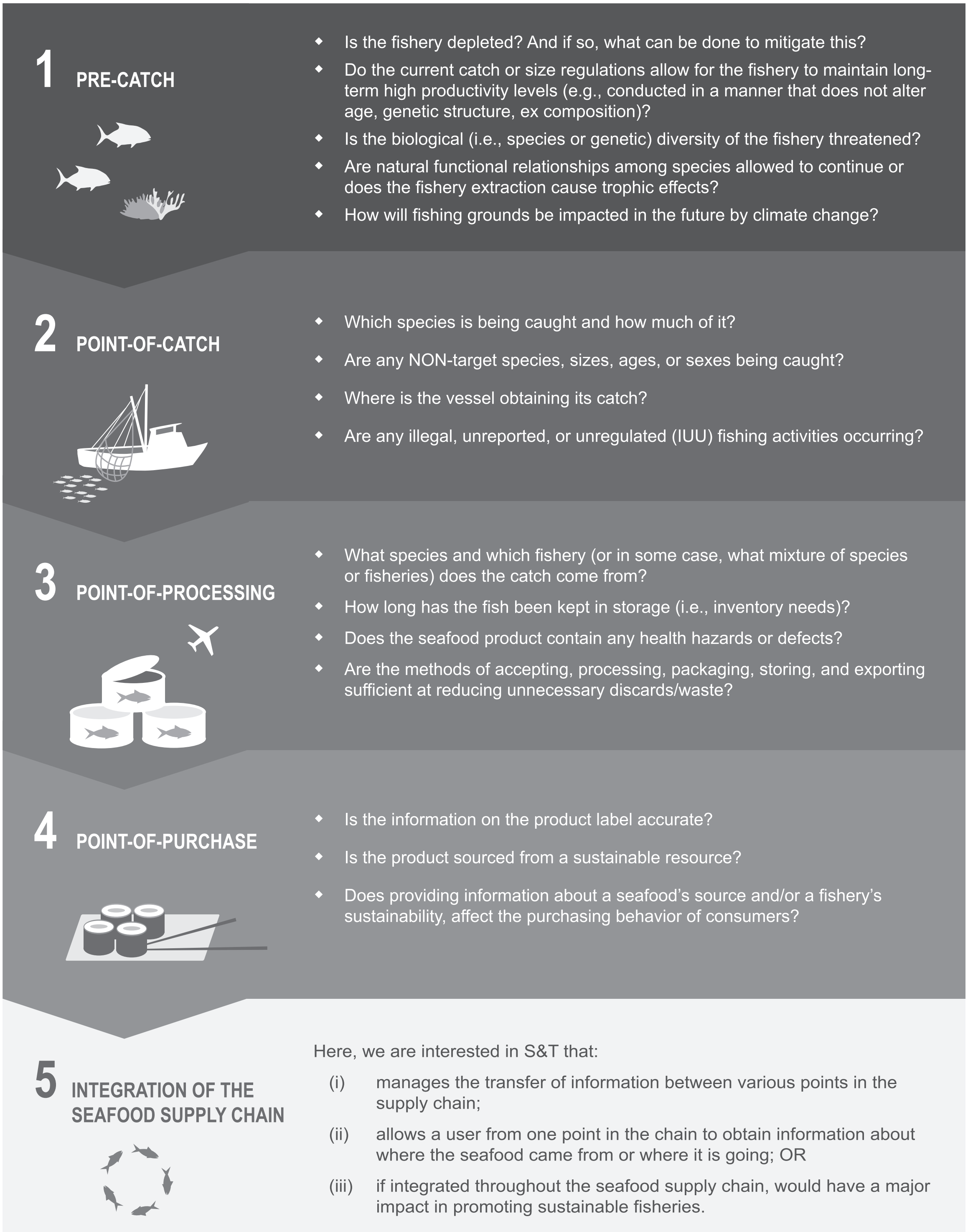

Fig. 1. Examples of fisheries management questions classified into five categories corresponding to different points on the seafood supply chain.

solutions presented in the survey (e.g., integrated ecosystem and socio-economic models, seascape ecology, etc.) may help to address some of these information needs, but received little support. On the one hand, the overwhelming support for stock assessments as an S&T solution may derive from a familiarity with the approach among the survey participants (i.e., NOAA and DOI managers and scientists). On the other hand, it also obliges us to recognize that single-species and integrated ecosystem assessments do not fall on opposite poles of a dichotomy, but rather on a continuum [21]. Therefore, as fisheries management in the CT/ASEAN region moves towards an EAFM, traditional stock assessment approaches should not be abandoned, but rather expanded to account for other biological, physical and socioeconomic components of the system.

Most importantly, EAFM data requirements should not be perceived as more cost-prohibitive when compared to traditional single-species stock assessments. In fact, collecting data on each individual targeted species under a traditional stock assessment program may itself be unrealistic, particularly in the CT region whose biodiversity of marine life and sheer number of targeted species is unmatched globally. Under an EAFM, however, the focus

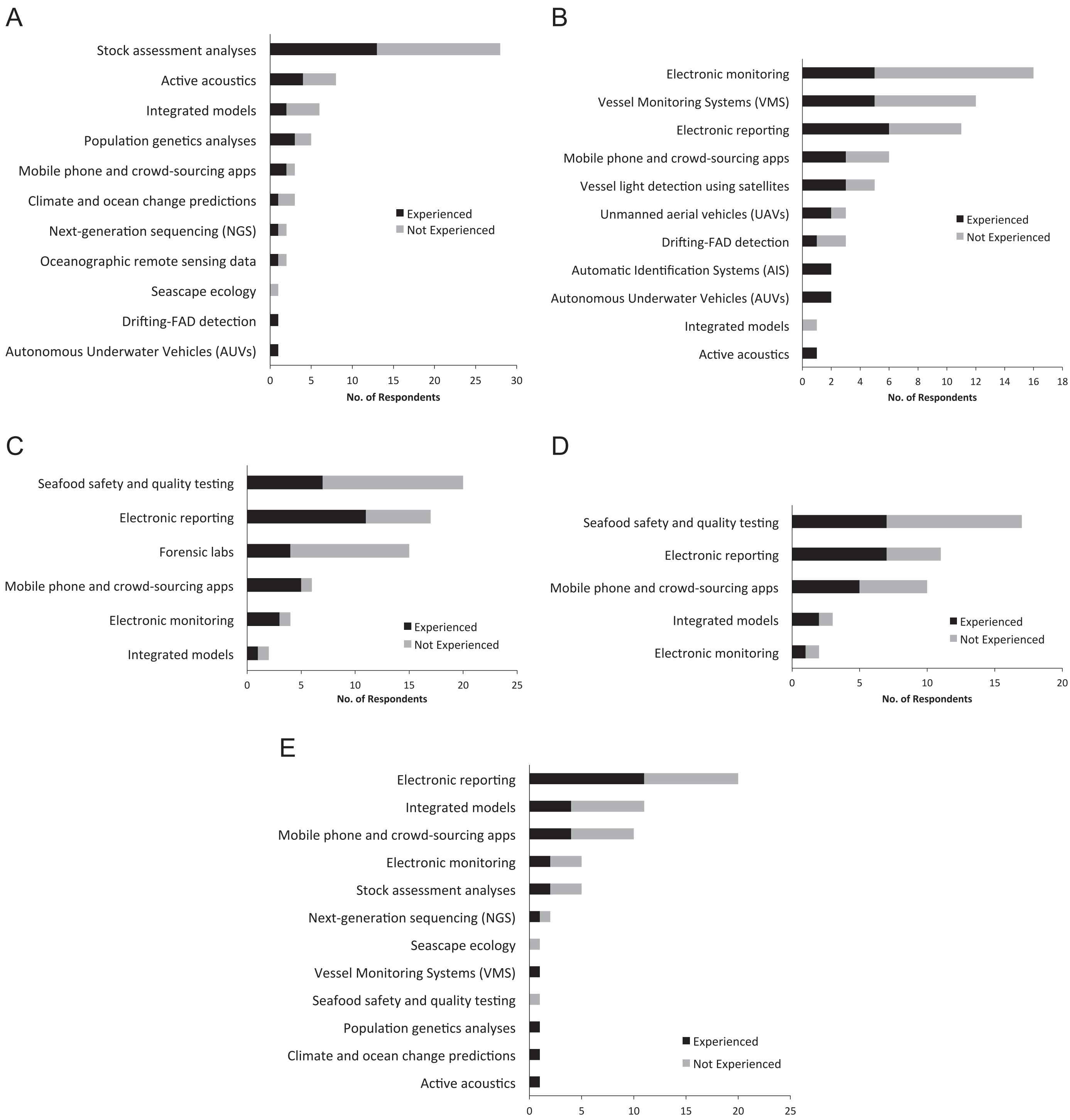

Fig. 2. Number of respondents that selected each of the different S&T innovations as being the most effective for improving management information needs at the (A) pre-catch, (B) point-of-catch, (C) point-of-processing or packaging, and (D) point-of-purchase. S&T innovations that can be used for integrating the entire seafood supply chain are shown in (E). Respondents that indicated that they were extremely or moderately experienced in or knowledgeable of Coral Triangle and Southeast Asia fisheries issues (black bars) vs those that indicated that they were only slightly or not at all experienced (gray bars) are also shown.

is moved away from having to collect data for each targeted species and instead moves towards ecosystem-level indicators [20] such as mean length for all species or the total biomass of different trophic groups. Additionally, indices that report on ecosystem status such as species richness, abundance of certain indicator species, or reef resilience indices may also become important under an EAFM. Similar to single-species methods that emphasize metrics such as maximum sustainable yield (MSY), the metrics under an EAFM should be accompanied with thresholds for regulation similar to the triggers used in single-species management.

For data-poor fisheries, scientists and managers in the region could focus on utilizing and/or developing data-limited approaches that can be used as stop-gap analyses until more data become available. Workshops that provide technical assistance and allow for international researchers to share their methods, develop best practices, and promote collaborations will be crucial (e.g., [8,9]). In the CT/ASEAN region, this type of workshop could be facilitated by ongoing regional exchanges as part of CTI and/or by SEAFDEC training programs. Furthermore, stock assessment programs could provide guidance on how best to prioritize S&T resources for future data collections based on the data requirements of the analyses.

Lastly, fisheries agencies must be willing to devote time and resources to scientific communication and outreach. Here, it is important to not only communicate the specific results from a stock assessment analysis, but to also educate stakeholders on the scientific information required for stock assessments and its credibility for guiding management recommendations. Stakeholder engagement and input are crucial to the success of an EAFM, and extra caution must be taken when implementing new or advanced S&T solutions to minimize the risk of marginalizing certain stakeholders. For this reason, stock assessment programs scientists in the region should consider employing participatory-based stock assessments (e.g., [43]). Fishers' experience with and knowledge of fish schooling behavior, habitat preferences at different life history stages, historical spawning grounds, and migration patterns have all proven to be valuable information about stock structure [1,18,24,26,27]. Working collaboratively and transparently on the stock assessment process will allow fishing industry constituents to gain a better understanding of the stock assessment process, resulting in better agreement on management recommendations.

5.2. Electronic reporting under an EAFM

As an S&T solution, electronic reporting (ER; i.e., a system of electronic logbooks) was given strong support by the survey participants for point-of-catch, point-of-processing, and point-of-purchase information management needs, as well as for integrating the entire seafood supply chain (Fig. 2B-E). Unlike catch landings data, which aggregate total catch for a single fishing trip, the implementation of at-sea logbooks allows for fishery data to be collected at finer temporal and spatial scales. Traditionally, this is done on paper; increasingly, however, ER is being implemented in fisheries around the world. ER is the use of technologies, such as phones or computers, to record, transmit, receive, and store fisheries data. Compared to traditional paper reporting systems, ER has the advantage of minimizing human-related errors (e.g., transcribing) and allows for faster data recording and data sharing, freeing up time for data verification purposes and bringing fisheries managers one step closer to near real-time fisheries management. On the other hand, skeptics of ER, point to the fact that self-reporting may not be accurate for rare or protected species [40]. In addition, intentional misreporting may come from distrust about the level of data confidentiality. In this case, captains may simply be unwilling to share the locations of good fishing grounds, especially if these data might inadvertently fall into the hands of their competition (i.e., other fishing fleets). While some studies have shown that self-reported logbook data are consistent with that of data collected by non-fisher third parties (e.g., fisheries observers; [41,17]), there are clearly incentives for fishers to misrepresent some of the data, and this continues to be a concern [38].

The problems associated with self-reported ER data, however, can at least be partially addressed when ER is implemented based on the guiding principles of an EAFM. First, industry representatives, including vessel captains and crewmembers, should be engaged early on, with their concerns about data confidentiality and security addressed from the beginning. Their buy-in will be crucial to the program's long-term success and thus, their input should be sought prior to the implementation of ER. In some cases, engagement alone may not be enough to motivate fishers to participate in ER programs, and incentives may need to be provided. In this case, the ER technology could be used to not only collect data, but also to provide accessible, up-to-date information on sea-state and weather conditions to the fishers. ER could also be used to keep a secure, historical log of past fishing grounds and catches to help vessel captains with planning future trips. In other words, the S&T should be used for two-way rather than one-way exchange of information [4]. Overall, efforts to engage industry stakeholders in the implementation of ER will help to resolve potential data recording problems as well as maintain enthusiasm and participation [19]. In some cases, these activities have led to an improvement in trust among scientists, fisheries managers, and fishers [2].

Lastly, ER should be designed to include a validation process that ensures data integrity. One method of doing this would involve cross-checking ER data at various points along the seafood supply chain. For example, self-reported catch data can be cross-checked with data on catch landings [38] or data collected by at-sea fisheries observers [45]. The coordination of data collection programs across sectors is one of the guiding principles of an EAFM, and ER is well placed to realize this. Crucially, ER should be implemented in a flexible manner, such that different users along the seafood supply chain are allowed to collect data specific to their needs (e.g., fishers collect point-of-catch data as part of their own record keeping of previously visited fishing grounds; further down the chain, seafood inspectors collect point-of-processing information regarding the temperature, condition, and overall quality of the shipment). Meanwhile, certain types of data (e.g., species ID, volume, most recent point of origin, and next point of destination) should be tracked throughout. This type of information sharing, across different points of the seafood supply chain, not only allows for cross-validation of the data collected at-sea, but could also provide the basis for catch documentation and traceability through the seafood supply chain.

5.3. Point-of-catch technologies under an EAFM

This next section briefly discusses two point-of-catch S&T innovations: mobile phone and crowd sourcing apps and vessel light detection using satellites. Both of these emerging technologies received moderate support from the survey participants, were not considered to be particularly cost-prohibited, and have already begun to hold promise for the region.

5.3.1. Mobile phones and crowd-sourcing apps

Mobile technologies (e.g., mobile phones and digital tablets) represent a relatively simple approach for collecting a high-volume of on-the-ground information. These devices can be used to integrate widely available technologies and hardware accessories (e.g., camera, GPS, accelerometer, etc.) as well as to access customized software (i.e., "apps") that allow for the automatic processing, analysis, and/or transmission of data. In the survey, this S&T solution was kept separate from electronic reporting (ER), which traditionally has been used by fishers, dealers, and/or seafood processors to report data on fishing trips, vessel identity, catch, landings, and purchases. On the other hand, mobile phones have been used for broader application in a fisheries context. It is certainly possible to merge ER with mobile phones as a single S&T solution. Indeed, due to the size and diversity of the fishing industry in the CT/ASEAN, implementation of any software-based technology would likely benefit from the use of multiple hardware platforms. Overall, mobile technologies show promise for fisheries data collection, particularly in remote areas. However, caution must be exercised when analyzing self-reported data, as the information was not collected at random according to a statistical design, and therefore may result in a biased representation of the fishery.

An important characteristic of CT/ASEAN fisheries is the vastness and anonymity of the artisanal fishing sector [25]. The lack of basic demographic information on artisanal fishers makes it difficult to formulate sound policy on human and health services, let alone fisheries management for this large sector of society. This is changing with the use of mobile phone technologies. For example, in the Philippines, the National Program for Municipal Fisherfolk Registration (FishR) allows fishers to register themselves and their fishing activities in a centralized database using a computer or mobile device. Previously, the process required fishers to report in person to a local government office. Prior to FishR, only 5% of the estimated 2 million small-scale fishers were registered, leaving the rest of the small-scale fishing sector largely unaccounted for. Within just 2 years, that number increased to more than 80%, or 1.5 million fishers. A major reason for the program's success is that registration comes with an incentive: access to certain government services such as health insurance and alternative livelihood opportunities. This once again demonstrates the importance of providing incentives to encourage stakeholder participation, particularly when the immediate benefit to the stakeholder is not apparent. Similar mobile phone programs have also been deployed in the Philippines to allow small-scale fishers to report illegal fishing activities. These violations are archived and passed on to local enforcement authorities, allowing for more rapid responses. Finally, in the Solomon Islands, a mobile phone application, Hapi Fis Hapi Pipol, allows surveyors to visit fish markets and collect data on the species and sizes of reef fish being sold; business operations, including purchases, prices, operating expenses; as well as demographic information on the fishers themselves. All of this information was previously unavailable to local fisheries managers but now has a chance to be incorporated into management decisions. Overall, mobile technologies have allowed for more holistic fisheries management and expanded stakeholder engagement in the region, primarily targeted towards small-scale fishers.

5.3.2. *Vessel light detection using satellites*

The NASA-NOAA Visible Infrared Imaging Radiometer Suite (VIIRS) has the capability to detect lit fishing boats at night. Typically, these are boats using light to attract catch, a widely used practice throughout East and Southeast Asia, as well as many other parts of the world [35]. Fishing lights are often used for small pelagic fishes such as sardines, herring, anchovies, scads, and squids. NOAA has developed algorithms for detecting and reporting the locations of such boats [11] and currently provides near real-time ($\sim$4 h latency) VIIRS boat detection services to several countries in the region. This capability can be used to identify potentially illegal fishing and to improve the management of fishery resources through the detection of fishing boats in fishery closure zones, protected coastal buffer zones, or Exclusive Economic Zone boundaries. The value of the VIIRS boat detections can be enhanced through cross correlation with vessel monitoring and tracking systems such as VMS and/or AIS (automatic identification systems). For example, nighttime fishing vessels that manage to turn off their VMS and AIS systems to avoid detection, presumably due to illegal fishing activities, could potentially still be detected by VIIRS. NASA and NOAA expect to launch the second VIIRS instrument in 2017 and have a long-term commitment to fly VIIRS sensors for an expanded number of years.

VIIRS is another good example of how S&T innovations will be most effective if implemented in the context of an EAFM. For example, managers who use VIIRS data would also benefit with the concurrent collection of data on other ecosystem factors. Doing so will enhance the utility of this technology since light detection alone will not inform managers of the types of fish being caught in these areas. Honing in on the specific catches of these nighttime fishers will require additional evidence, either by correlating the movements of nighttime fishers with data on fish habitat and fish behavior or by directly engaging both commercial and artisanal fishers of these areas.

Furthermore, the use of VIIRS must be coordinated on multiple scales. In response to illegal fishing activities detected with VIIRS, multiple countries in the region could coordinate their enforcement activities on an international level. As national governments work to coordinate their efforts, they should not, however, forget to engage local government units and explore the possibility of community-based surveillance programs. Anecdotal evidence shows that compliance on fisheries regulations is higher when enforcement is shared at both the local and national-level. A combination of empowered local leaders and community-mediated peer pressure has the ability to actually influence fisher behavior [7], an important result when trying to achieve long-term sustainable fisheries. Co-management systems that empower local communities to be engaged in enforcement activities may be especially appropriate when the national government's enforcement capabilities are inadequate. Thus, advanced technologies such as VIIRS or other satellite-based surveillance systems should be seen as complementary to community-based surveillance programs, and implemented and coordinated across multiple scales of governance.

6. Conclusions and main recommendations

The countries of the CT/ASEAN region have recognized the need for increased coordination and cooperation in the management of their marine resources. Support for an EAFM has been declared at both national and regional levels, and progress is being made with the development of regional management plans founded on EAFM principles. This progress bolsters the assertion that the implementation of an EAFM is possible, even in data-limited contexts and poor governance structures [28,42].

It should be emphasized that the S&T innovations identified by this study are specific to one set of stakeholders, namely U.S. government fisheries and conservation experts. Their interest stems from their role as consumers in the global seafood supply chain as well as an international interest in combatting IUU fishing. The limited scope of this study, however, prevents the generalization of results to the opinions of fisheries managers in the CT/ASEAN region. Regardless of which S&T innovations are implemented, however, a review of the literature as discussed above revealed several common themes regarding the intersection of S&T innovations and an EAFM. When implementing S&T innovations within an EAFM context, the following five main recommendations were identified:

(1) Treat all stakeholders as scientific partners. They should come to understand the goals of the S&T's implementation and the importance of standardized data collection for ensuring that the scientific process is unbiased. Stakeholder education on these matters is essential to cultivating transparent relationships, which itself is key to the S&T's perceived credibility among stakeholders. For example, in the implementation of electronic reporting and/or mobile phone and crowd-sourcing technologies, fishers should be engaged prior to the S&T's implementation to ensure accurate and continued participation in the data collection activities. Similarly, stock assessment programs should consider the use of participatory stock assessments that incorporate the traditional knowledge of fishers into their analyses.

(2) Expand data collection activities to include wider ecosystem components. For example, fisheries managers who hope to use VIIRS or other advanced technologies in surveillance activities should also take steps to collect additional ecosystem components (e.g., characterization of fish habitat in areas with fishing nightlight activities to provide context to nightlights data). Similarly, stock assessment analyses can be more holistic in their consideration of environmental drivers that affect fisheries.
(3) Coordinate the S&T's implementation across scales and sectors. For example, the utility of electronic reporting as a data collection tool can be enhanced by standardizing this platform across different sectors of the seafood supply chain to create effective catch documentation and traceability. Similarly, the utility of VIIRS as a surveillance tool is enhanced when enforcement activities are shared at both national and local levels of government.
(4) Incentivize stakeholder participation by creating connections between their well-being and/or livelihood and the S&T's implementation. For example, in implementing ER, additional incentives could be provided to participating fishers in the form of accessible, up-to-date information on sea-state and weather conditions. Another example would be the implementation of the mobile phone and crowd-sourcing app, FishR, to register small-scale fishers with the Philippines government. In this case, participating fishers gained access to important government health services, and this is was a clear incentive for them to participate.
(5) Promote the two-way exchange of information. Tension or mistrust can arise when S&T only facilitates the one-way flow of information. This can be mitigated by ensuring that the information collected by the S&T innovation is shared among stakeholders. For example, catch data collected by ER could be archived as a historical record of fishing grounds, which vessel captains could use for planning future fishing expeditions. Similarly, the results of stock assessment analyses should be communicated back to all stakeholders. The more fisheries programs are able to devote to supporting and/or developing science communication and outreach skills, the greater the consensus they will be able to achieve among stakeholders.

If implemented properly, S&T innovations have the potential to enhance cooperation and coordination of marine resource management efforts as well as promote stakeholder engagement and inclusiveness. The implementation of S&T should be guided by the principles of an EAFM. Doing so will strengthen the salience, credibility, and legitimacy of the scientific information used for fisheries management, and minimize competing and conflicting stakeholders' concerns [3]. Just as is advocated for by an EAFM, the implementation of S&T should be inclusive and holistic, both in terms of the types of information collected and analyzed (i.e., the physical, biological, and human components of the system) as well as the user groups it benefits.

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Appendix

Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis for: (A) stock assessment analyses, (B) electronic reporting, (C) mobile phones and crowd-sourcing technologies, and (D) vessel light detection using satellites. Strengths and opportunities, refers to the characteristics of the technology that place it at an advantage or disadvantage, respectively, over other similar technologies. Opportunities and threats, refers to the characteristics of infrastructure (political, institutional, physical, or human resources) that could potentially advance or hinder, respectively, the successful implementation of the technology in the Coral Triangle and Southeast Asia region.

(A) Stock assessment analyses

Strengths:

- Scientific training in stock assessment will not become outdated; foundational knowledge will be needed even as stock assessment models continue to develop.
- A range of stock assessment methods is already available for data-poor fisheries.
- Stock assessments can be implemented using standard computing power and software packages that are free and open-source.

Weaknesses:

- Stock assessment science is a rich and diverse field; a successful training program needs to be relatively comprehensive and could potentially have a steep learning curve.

Opportunities:

- Training programs facilitate communication and establish partnerships.
- Stock assessment programs can provide guidance to on-going or future data collection activities based on the data needs of the analyses.

Threats:

- Stock assessment science is a specialized and dynamic field requiring a relatively strong background in mathematics and statistics; creating a stock assessment program will require a sustained commitment to developing, recruiting, and maintaining a cadre of technical experts.

(B) Electronic Reporting

Strengths:

- Timely data reporting will allow for more dynamic and adaptive monitoring and management.
- Systems can be designed to have quality control checks in place, thus allowing for automated data validation; in addition, ER eliminates the transcription (paper to computer) step and any errors associated with it.

Weaknesses:

- Data will still only be as accurate as the information provided and could be intentionally or unintentionally inaccurate.

Opportunities:

- ER technologies if fully integrated across the industry and validated throughout with a clear and secure "chain of custody" (e.g., e-signatures) can be used to achieve catch documentation and traceability in the seafood supply chain.
- There could be an opportunity for government and industry stakeholders to collaborate on the implementation of the technology.

Threats:

- There could be potential resistance from industry to new or unfamiliar technology, or due to concerns over data confidentiality issues.
- The financial cost for installing, securing, and operating electronics on fishing vessels and for receiving, analyzing, and archiving data could be prohibitive.

(C) Mobile phones and crowd-sourcing technologies

Strengths:

- Several examples of this technology have already demonstrated success in engaging small-scale, subsistence fishing communities in remote, isolated, and data-poor areas.
- New hardware technologies allow for diverse data collection capabilities (e.g., camera/microscope, temperature sensor, light sensor, digital barometer, altimeter, accelerometer, gyroscope, etc.).

Weaknesses:

- Crowd-sourced data is not collected according to any sort of statistical design, and therefore caution must be used in its interpretation.

Opportunities:

- Small-scale, developing country fishers have used cell phone/text message functionality to find the best markets and get better prices for their products, resulting in a more efficient market and less wasted fish.
- There is an opportunity to coordinate this technology with electronic reporting systems for data collection purposes.

Threats:

- The subsequent increase in data may overwhelm the ability for government agencies and others to analyze and manage the information.

(D) Vessel Light Detection using Satellites (i.e., NASA/NOAA's Visible Infrared Imaging Radiometer Suite)

Strengths:

- NOAA's National Geophysical Data Center collects and archives the data for public use.

Weaknesses:

- Additional evidence or documentation would be needed to characterize the fishing activity.
- Boats may evade detection by turning off their lights for satellite overpasses.

Opportunities:

- The data is already being operationalized by fisheries agencies in the Philippines and Indonesia.
- There is an opportunity for multiple countries in the region to collaborate on the use of this technology to manage transboundary marine resources.

Threats:

- Data are not real-time; currently there is a $\sim$4 h temporal lag.

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