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Effects of indiscriminate fisheries on a group of small data-poor species in Thailand

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As catches of economically valuable target fishes decline, indiscriminate fisheries are on the rise, where commercial and small-scale fishers retain and sell an increasing number of marine species. Some of these catches are destined for international markets and subject to international trade regulations. Many of these species are considered “data-poor” in that there are limited data on their biology, ecology, and exploitation, which poses a serious management challenge for sustainable fisheries and trade. Our research explores the relative pressure exerted by such indiscriminate fisheries on a data-poor marine fish genus—seahorses (*Hippocampus* spp.)—whose considerable international trade is regulated globally. Our focus is Thailand, a dominant fishing nation and the world's largest exporter of seahorses, where we gathered data by interviewing commercial and small-scale fishers and through port sampling of landed catch. We estimate that annual catches were more than threefold larger than previously documented, approximating 29 million individuals from all gears. Three fishing gears–two commercial (otter and pair trawl) and one small-scale (gillnet)–caught the most individuals. Results from port sampling and our vulnerability analysis confirmed that *H. kelloggi*, *H. kuda*, and *H. trimaculatus* were the three species (of seven found in Thai waters) most susceptible to fishing. Small-scale gillnets captured the majority of specimens under length at maturity, largely due to catches of juvenile *H. kuda* and *H. trimaculatus*. This research indicates a role for vulnerability analysis to initiate precautionary management plans while more extensive studies can be conducted.

Keywords: CITES, data-poor, fisheries management, seahorses, Thailand, vulnerability analysis.

Introduction

The pressure on non-target species from fisheries remains a serious problem (Davies *et al.*, 2009). Many non-target species, such as juvenile fish, shellfish, and invertebrates, are incidentally captured in fishing gears around the world (Davies *et al.*, 2009). In many fisheries, non-target species, once considered a nuisance by fishers, are becoming incorporated as part of target catches (FAO, 2012). The availability of new markets are driving this practice because non-target species are being used to make products such as animal feeds or fertilizers (FAO, 2012). These markets provide additional revenue for fishers and little incentive to reduce amounts of non-target catch, turning these fisheries into indiscriminate fisheries (FAO, 2012). As a result, both commercial and small-scale fishers are taking and utilizing an increasing number of species, with many non-target species becoming targeted. With the additional threats to the marine environment such as coastal run-off, sedimentation, and changes in water quality (Fabricius, 2005), maintaining healthy populations of an increasing number of target species remains an elusive task (Costello *et al.*, 2012).

Because catch from small-scale and commercial fishers enters the market, some of which falls under international regulation (UNEP-WCMC, 2012), countries must determine how to manage such indiscriminate fisheries sustainably (CITES, 2013). The sustainable management of national fisheries must include the social, economic, and biological nature of fisheries (Gerrodette *et al.*, 2002; Salomon *et al.*, 2011). The intersection of national fisheries management, species conservation, and international trade becomes even more complicated (Joseph, 1994; Vincent *et al.*, 2014) due to issues linked to national sovereignty, conflicting mandates, and multiagency and organization involvement in these issues (Joseph, 1994; Vincent *et al.*, 2014). Every country has the right to manage its own natural resources, but the vast majority of countries have also agreed to international treaties related to sustainability, such as the Convention on International Trade in Endangered Species (CITES) (CITES, 2013). By agreeing to international treaties, countries have accepted the obligation to implement these treaties at the national level (Joseph, 1994).

Determining fisheries management solutions to address increasing pressures on species captured by indiscriminate gear is challenging, primarily due to lack of data for rigorous analysis (Reuter *et al.*, 2010). Many fisheries remain unassessed and unmanaged because natural resource managers lack the data to perform both simple and complex stock assessments (Honey *et al.*, 2010; Costello *et al.*, 2012). Typical fisheries management at the very least requires information on catches and fishing effort (Walters and Martell, 2002), which can be hard to obtain for data-poor species. Stock assessments typically guide the fisheries decision-making process by providing an understanding of fish population dynamics in relation to fishery input (e.g. number of fishing vessels) or output controls (e.g. total allowable catch, quotas) (Sparre and Venema, 1998). However, even fish stocks with the necessary data to perform various stock assessments can be mismanaged or suffer from poor data quality (Walters and Maguire, 1996; Myers *et al.*, 1997). With decreasing abundance of many marine species (both large and small) (Hutchings *et al.*, 2010), waiting for data to become available may be detrimental to sustainable management (Johannes, 1998). How then should management decisions be made for data limited species?

Several new methods for dealing with data-poor stocks (Patrick *et al.*, 2009; Honey *et al.*, 2010; Reuter *et al.*, 2010) have been proposed recently, but have yet to be evaluated in many national and international contexts. For example, international conventions, such as CITES, require data at the very least on species and fisheries, as do many national-level policies (UNEP-WCMC, 2012; CITES, 2013). Specifically to identify pressure from fisheries, CITES recommends looking at the (i) diversity of fishing methods/gears, (ii) fishing mortality, (iii) fishing selectivity, (iv) discarding practices, and (v) indicators of fishing impacts. However, there is little guidance on the spatial or temporal nature of such data or appropriate analytical techniques required to evaluate the pressure on species from fisheries, as is true in many countries (CITES, 2013). A recent review of data-poor fishery assessment methods outlines various methods based on data richness (Honey *et al.*, 2010) and ranges from stock assessment methods (Rago and Sosebee, 2010; Carruthers *et al.*, 2014) to vulnerability analyses (Patrick *et al.*, 2009; Brown *et al.*, 2013) and extrapolation methods (Smith *et al.*, 2009). Vulnerability analyses have the potential to be a good compromise at both national and international levels between the more data-intensive assessment methods such as stock assessment and the least data-intensive methods like extrapolation (Honey *et al.*, 2010; CITES, 2013).

The future of seahorses (*Hippocampus* spp.), a marine fish genus captured indiscriminately in many fisheries around the world, lies at the nexus of conservation, fisheries, and international trade. Traded internationally for use in traditional medicine and aquariums (Vincent *et al.*, 2011), seahorses were the first marine fishes to be listed on CITES Appendix II since its inception, and the first marine fishes on the Convention to have countries undergo the enforcement process (UNEP-WCMC, 2012; Vincent *et al.*, 2014). As part of the enforcement process, any country exporting an Appendix II species is required to determine if trade is detrimental to wild populations (UNEP-WCMC, 2012). CITES trade records indicate seahorse trade volumes range between 3.3 and 7.6 million individuals annually, but most likely under-estimate actual trade volumes due to reporting challenges (Foster *et al.*, 2016). From a fisheries perspective, annual estimates of bycatch suggest that 39 million seahorses are captured by global fisheries each year (Lawson *et al.*, 2017). The trade of seahorses is global and complex, involving 25 of 41 known species, and more than 80 countries (Foster *et al.*, 2016; Lourie *et al.*, 2016). However, more than half of species in trade (20 of 41) are listed as “Data-Deficient” by the IUCN, meaning there is not enough information about their population status, distributions, or threats to evaluate extinction risk (IUCN, 2015). Because of the limited global seahorse knowledge, determining if national level seahorse exports are detrimental to local populations remains challenging (CITES, 2013).

As the world‘s largest exporter of seahorses, Thailand has undergone the CITES enforcement process twice to determine if their seahorse exports were detrimental to wild populations. Thailand has faced challenges related to insufficient data regarding the seahorse species and fisheries involved in the trade, making an evaluation of impact to local populations difficult (UNEP-WCMC, 2012; CITES, 2013). CITES export records, despite their shortcomings, indicate that Thailand accounts for 75% of global seahorse exports, with annual estimates between 3 and 6 million seahorses in 2004–2012 (Foster *et al.*, 2016). Seven out of the 14 seahorse species found in Southeast Asia live in Thai waters, with five reported in trade (Perry *et al.*, 2010). All five trade species have national and global assessments documenting a “vulnerable” risk of extinction (Vidthayanon, 2005; IUCN, 2015) caused by habitat loss and bycatch in incidental and target fisheries. Importantly, little is known about how seahorses in Thailand are influenced by fisheries. Thailand is home to many small-scale and commercial fisheries representing a range of fishing gears (Lymer *et al.*, 2010; FAO, 2012), and catch of seahorses for dry trade has been documented in both types of fisheries (Laksanawimol *et al.*, 2013). Previous research in the late 1990 s estimated Thailand‘s trawl fleet caught ca. 2 million seahorses per year, but this study did not investigate catch rates for any other commercial or small-scale gears (Perry *et al.*, 2010). Identifying appropriate methods to evaluate Thai fisheries with minimal data in relation to local seahorse populations will support Thailand to identify which species and gear to focus management measures, and comply with CITES implementation. The goal of our research was to estimate the annual catch of seahorses in small-scale and commercial fisheries in Thailand and characterize the catch of different fishing gears on these data-poor fishes. Additionally, we explore the use of vulnerability analysis as a data-limited fishery assessment method to identify which seahorse species is most at risk of overfishing.

Material and methods

To estimate the annual catch of seahorses and better understand how indiscriminate fisheries affect a group of data-poor fishes, we interviewed fishers and executed port sampling of seahorses throughout coastal Thailand. Although Thai fishers keep logbooks and landings data for species with commercial value, they do not record such data for seahorse catch; therefore, interviews were identified as the best way to elicit information. We conducted our research with the support of the Thailand Department of Fisheries (DoF), seeking input on where to collect data based on locations representative of local fishing activities. We first describe the methods used to collect the data and then describe the analyses used to (i) estimate annual seahorse catch, (ii) characterize the seahorse catch of different fishing gears, and (iii) conduct a vulnerability analysis to identify which species is most at risk.

Data collection

To identify what fishing gears and seahorse species were captured by indiscriminate fisheries, we conducted semi-structured fisher interviews in 11 provinces on both the Andaman ($n = 6$) and Gulf ($n = 5$) coasts of Thailand. Interviews were semi-structured in nature because fishers were asked different questions depending on their initial responses and/or responsiveness. We interviewed a total of 306 (137 commercial and 169 small-scale) fishers from both coasts. Since commercial and small-scale fisheries have defining characteristics in Thailand, such as boat size, ice storage, and distance fished from shore (Lymer *et al.*, 2010), we expected their annual seahorse catches to differ. We focused our sampling efforts on four types of commercial gears (otter trawl, pair trawl, purse-seine, pushnet) and two types of small-scale gears (gillnet, cage) based on recommendations of dominant gear types from the DoF.

To select respondents, we targeted two sets of landing locations: (i) fishing ports for commercial fishers and (ii) coastal villages for small-scale fishers. Commercial fishing port locations were identified as ports located near government port facilities, whereas landing locations in coastal villages were typically on local beaches or in an estuary near fishers' houses. We visited a total of 13 ports (Andaman = 7, Gulf = 6) and 28 coastal villages (Andaman = 21, Gulf = 7) (Figure 1). We determined the number of fishers to interview in each location as either 10% of the estimated total number of fishing boats landing catch at that location or the saturation method (Tobias, 2010), given our need to maximize the number of landing locations visited. We defined saturation as the point where if the 6th, 7th, and 8th interviews introduced no more new information on gear type, fishing grounds, or seahorse locations, then saturation had been achieved. We additionally confirmed saturation through our observations of gear type at each landing location. All interviews followed UBC Human Ethics Protocols (H12-02731).

During semi-structured interviews (Stake *et al.*, 2005), we asked fishers about the frequency and duration of their fishing activities. Fishers were asked to describe gears, depths fished, number of hauls (or sets) per day, and typical fishing duration per day, month, and year. We asked fishers to identify the gears they use that capture seahorses, along with numbers and frequency of catch. We offered fishers the opportunity to report seahorse catch by haul, day, fishing trip, week, month, or year. Fishers could report catch for more than one effort estimate, for example, some fishers report mean seahorse catch per day and also per month. This type of reporting would enable us to scale catches up to annual estimates based on additional information gathered throughout the interview on number of hauls per day, total days fished per month, and total months fished per year.

To identify what gears and seahorse species were involved in seahorse catch, we conducted port sampling opportunistically while at landing locations conducting fisher interviews. When we encountered seahorses in a fisher's catch, the species, size, and sex were determined from all available individuals in the catch. Seahorses were then returned to the fisher to retain, discard, or sell.

To identify the total number of registered fishing vessels by gear type, we accessed the most recent fisher census data from the Thailand Department of Fisheries (www.platalay.com/boatsurvey2554/index.php). Within the census data, small-scale and commercial fishing gears were categorized by gear type and reported by province. We summarized the available numbers for our six focal gears at the provincial level to create national totals for each gear type: (i) otter and (ii) pair trawls, (iii) purse-seines, (iv) pushnets, (v) gillnets (including surrounding nets) for fish, crab, and shrimp, and (vi) cages (for fish, crab, and squid).

Analysis

Estimating current annual catch

First, we calculated annual catch rates for each fisher by scaling up his/her reported mean catch rate with his/her reported frequency of fishing (e.g. daily catch rate $\times$ total days fished per month $\times$ total months fished per year). For those fishers who reported more than one catch rate (e.g. fishers reporting catch rates per day and per month) ($n = 42$), we selected the catch rate for the longer period of time (e.g. per month) because many fishers upon reflection ($n = 40/42$) adjusted their estimated catch rate for the longer period of time to account for zero catches. We assumed that all catch was landed because 96% of commercial and 75% of small-scale fishers reported retaining seahorse catch to sell (L. Aylesworth, pers. comm.). We explored the potential for recall bias and geographical differences in fisher-reported catch rates and found that mean reported catches, rather than any one specific reporting time-period, were corroborated with external data (Aylesworth and Kuo, under review).

Calculating annual catch by gear type was a two-step process. Because there was high variation in fisher-reported catch rates, we determined the percentage of fishers reporting no yearly catch and made the assumption that the fleet (for each gear) had the same proportion of zero catch. For the positive catches per year (where fishers reported catch rates > 0), we used the mean catch rate per vessel and their associated 95% confidence intervals. For the lower bounds of the 95% confidence interval, if the value was zero because of high levels of variation, we assumed a mean catch rate of 1. Second, to calculate yearly catch, we multiplied the mean catch rate per vessel by the proportion of the fleet size with positive catches. We used vessel numbers as a proxy for scaling effort nationally because other information such as total trips or total effort days per gear type was unavailable. We used 95% confidence intervals from mean catch rates per vessel to determine 95% confidence intervals at the fleet level. Additionally, we summed each annual catch estimate and its associated 95% confidence interval for all gear types to determine a national estimate of seahorse catch.

We made four key assumptions in the development of our Thai national estimate of seahorse catch. First, we assumed that fishers had a consistent catch for all seasons. Second, we assumed that individual fisher catch rates did not differ spatially with fishing ground location. Third, we assumed that fishers were reporting current effort and catches. Fourth, we assumed that the number of fishers reporting zero catch per gear type was proportional to the number of vessels across the entire fleet with zero catch.

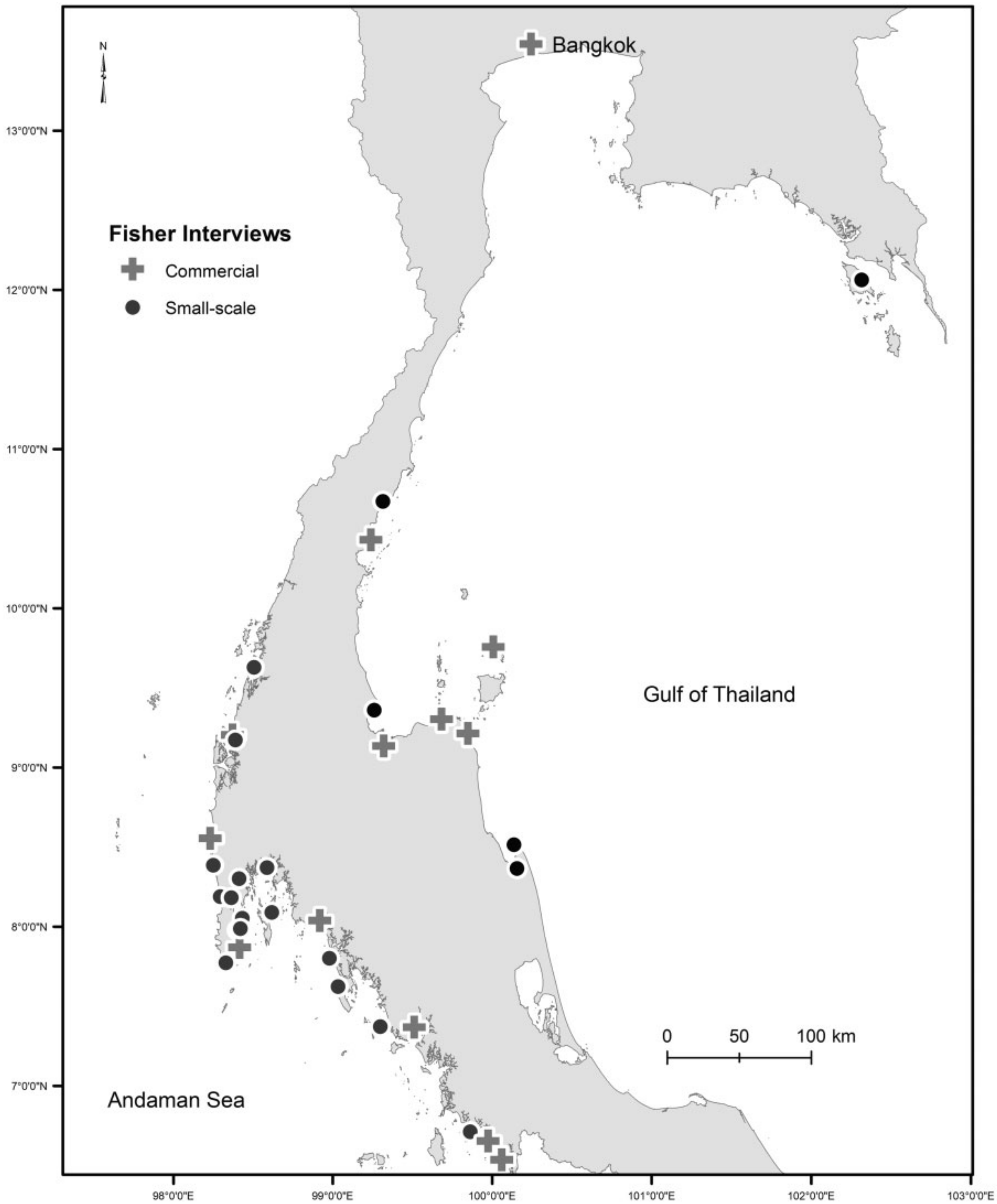

Figure 1. Locations of fisher interviews with commercial and small-scale fishers along Thailand's coast.

Characterizing fishing gear catch

To characterize the catch from our six different fishing gears on seahorse stocks, we summarized the port-sampled data by gear type and species. We then compared the results from port sampling to annual seahorse catch rates per vessel from fisher interviews. Additionally, we looked for indicators of overfishing by gear type and species by calculating the majority of sampled catch under length at maturity and the presence of sex bias in the catch. Identifying the gear with the greatest percentage of catch under height at maturity can be an indicator of high risk of overfishing (Froese, 2004), as can sex ratios significantly different from unity (Rowe and Hutchings, 2003). However, these assumptions are linked to fishing selectivity, and assume that fishing mortality is high and/or that adults are vulnerable to fishing (Cope and Punt, 2009). We sourced lengths at maturity from FishBase (2016) for *H. histrix, H. kelloggi*, and *H. kuda* and from Lawson *et al.*, 2015 for *H. spinosissimus* and *H. trimaculatus*. The values from Lawson *et al.* (2015) were empirical estimates from stocks in peninsular

Table 1. Life history indicators for the five Thai seahorse species (*Hippocampus* spp), observed in port sampling.

***Hippocampus* spp. (common names)**	***n* (from port sampling)**	**Population growth rate ($1\ year^{-1}$)**	**Max height (cm)**	**L_∞ (cm)**	**von Bertalanffy growth coefficient (k)**	**Natural mortality (M) (%)**	**Maximum age (years)**	**Height at reproductive maturity (cm)**	**Age at first maturity (years)**	**Mean trophic level**
H. histrix (Thorny seahorse, longspine seahorse)	2	1.059	17.0	18.0	0.81	1.61	3.5	11.2	1.0	3.5
H.kelloggi (Great seahorse, Kellogg's seahorse)	67	1.047	28.0	29.4	1.04	1.95	2.7	15.0	0.7	3.4
H.kuda (Spotted seahorse)	71	1.131	17	21.9	2.47	3.93	1.1	14.0	0.3	3.6
H. spinosissimus (Hedgehog seahorse)	97	1.053	22.7	23.9	0.97	1.86	2.9	12.3*	0.7	3.4
H. trimaculatus (Three-spot seahorse, longnose seahorse, smooth seahorse)	261	1.061	22.0	23.2	1.01	1.83	2.9	12.1*	0.8	3.8

All indicators taken from FishBase (2016) except for those heights at reproductive maturity estimates indicated with *, which came from Lawson et al. (2015).

Malaysia, whereas the values taken from FishBase (2016) were generated with the life history tool, despite its potential for bias (Thorson *et al.*, 2014). We used a Chi-squared test to identify if sex ratios by gear type and species were significantly different from unity ($p < 0.05$) (Zar, 1999).

Vulnerability analysis: which species is most at risk?

To further understand the pressure exerted on seahorse stocks by indiscriminate fisheries, we executed a vulnerability analysis, one of the recommended data-limited fishery assessment methods (Honey *et al.*, 2010). We modified a productivity-susceptibility analysis (PSA) (Stobutzki *et al.*, 2001; Patrick *et al.*, 2009) based on the data available for seahorses in Thailand, which enabled us to incorporate life history of each species with the data available from fisher interviews and port sampling. A typical productivity-susceptibility analysis ranks multiple species with respect to susceptibility to fishing and the stock‘s capacity to recover after depletion (typically life history characteristics) (Stobutzki *et al.*, 2001). The rank represents the stock‘s relative capacity to sustain fishing and can be used to determine fisheries management priorities (Patrick *et al.*, 2009). This method of analysis is growing in its use to assess data-poor bycatch species (Patrick *et al.*, 2009; Brown *et al.*, 2013). We piloted this method for its relevance to a group of five small congeneric fishes, since typically PSAs compare species with a wide breadth of life history characteristics (e.g. gobies to sharks) (Stobutzki *et al.*, 2001; Patrick *et al.*, 2009).

We identified productivity attributes of the five seahorse species represented in port sampling from FishBase (2016) or new literature (Lawson *et al.*, 2015) for the following characteristics: population growth rate, maximum length ($L_{\max}$), maximum asymptotic length (L_∞), von Bertalanffy growth coefficient (k), natural mortality (M), life span, length at maturity, age at maturity, and mean trophic level (Table 1). The original PSA contained seven attributes to evaluate susceptibility to the fishery, such as water column position or probability of survival after interaction with fishing gear (Stobutzki *et al.*, 2001), but this information either did not differ among seahorse stocks (e.g. water column position) or is unknown for all seahorse species (e.g. probability of survival with fishing gear). Therefore, we created our own susceptibility attributes based on data available in Thailand (Table 2). As commonly done in productivity and susceptibility analysis (Stobutzki *et al.*, 2001; Patrick *et al.*, 2009), we divided the range in attributes of our five species for both productivity and susceptibility to fishing into three categories for each variable with scores representing low (1), moderate (2), and high (3) risk (Table 2). We anchored scores around median values, which were assigned to the moderate (2) risk category (Stobutzki *et al.*, 2001; Patrick *et al.*, 2009), and weighted all attributes equally. We then summarized the values and divided by the number of total attributes to determine an average score from 1 to 3 for life history (1 = high productivity, 3 = low productivity) and fishing pressure (1 = low pressure from fishing, 3 = high pressure from fishing) (Table 2) (Stobutzki *et al.*, 2001; Patrick *et al.*, 2009). We conducted a sensitivity analysis on the division of productivity risk categories based on the 14 seahorse species found in Southeast Asia (Supplementary Material, Section 1). Averaged scores for productivity and susceptibility were categorized as follows ≤ 1.5 = low risk, 1.6–1.9 as moderate risk, and ≥ 2 as high risk. Similar to Patrick *et al.* (2009), seahorses with a higher

Table 2. Productivity and susceptibility attributes for five Thai seahorse species and risk categories (modified from Stobutzki *et al.*, 2001 and Patrick *et al.*, 2009).

	Attribute	Low risk (Score 1)	Moderate risk (Score 2)	High risk (Score 3)
Life history "productivity"	Population growth rate (1 year^{-1})	>1.08	1.05–1.08	<1.05
	Maximum height (cm)	<20	20–25	>25
	von Bertalanffy growth coefficient (1 year^{-1})	>2	1–2	<1
	Estimated natural mortality (%)	<2	2–3	>3
	Maximum age (years)	<2	2–3	>3
	Age at maturity (years)	<0.4	0.4–0.8	>0.8
	Mean trophic level	<3.5	3.5	>3.5
Fishing pressure "susceptibility"	% of port sampled catch	<25% of port sampled catch	25% < port sampled catch <50%	>50% port sampled catch
	% catch under length at maturity	<33% catch over length at maturity	33% < catch over length at maturity < 67%	Catch over length at maturity >67%
	Sex bias in catch	No	—	Yes
	Fleet size	<1 000	1 000-10 000	>10 000
	Mean catch rate (per year for 1 vessel)	<200	200-1 000	>1 000

productivity risk were not be considered vulnerable to fishing unless there was also some susceptibility to fishing.

Results

Estimating current annual catch

Catch rates vessel^{-1} year $^{-1}$ ranged from 106 to 6534 seahorses (Table 3). Otter and pair trawl gears had the highest catch rates vessel^{-1} year $^{-1}$, in the thousands, out of all fishing gears (Table 3). Commercial pushnets and small-scale cages had the lowest catch rates vessel^{-1} year $^{-1}$ (less than 200) for each of these types of fisheries (Table 3). Out of small-scale fishing gears, gillnets had catch rates ca. double those of cages (Table 3). All gears had high variation in reported in catch rates vessel^{-1} year^{-1} (Table 3).

We estimated that the annual number of seahorses captured by Thai fishing gears was 29.0 million seahorses (95% confidence interval: 5.0–55.1 million) (Table 3). Annual estimates of seahorses by fishing gear type ranged from 78 419 (pushnets) to 13 551 274 (otter trawls) (Table 3). Pair trawls and gillnets both had large annual estimates (in the millions), whereas purse-seines, pushnets, and cages all had annual estimates less than 500 000 (Table 3).

Characterizing fishing gear catch

Port sampling results confirmed the results of fisher interviews that otter trawls, pair trawls, and gillnets caught the greatest amount of seahorses (Table 3). A total of 498 ($n = 251$ Andaman, $n = 247$ Gulf) seahorses were port sampled from 55 ($n = 25$ Andaman coast, $n = 20$ Gulf coast) fishers. Purse-seines, pushnets, and cages had the lowest sample sizes of port sampling, with each gear having five or fewer individuals.

In terms of indicators of overfishing risk, small-scale fishing gears had the greatest percentage of catch under length at maturity (Table 3). For commercial gears, purse-seines (20%) and pair trawls (15%) caught the highest amounts of catch under length at maturity, whereas pushnets had the lowest (0%) (Table 3). No gears had sex ratios significantly different than unity (all $p > 0.05$) (Table 3).

We recorded five seahorse species during port sampling: *H. histrix, H. kelloggi, H. kuda, H. spinosissimus*, and *H. trimaculatus* (Table 4). Our results indicate that most seahorses in sampled catches were *H. trimaculatus* (Table 4). We recorded *H. histrix* the least frequently (Table 4). The species captured in the greatest diversity of fishing gears were *H. spinosissimus* and *H. trimaculatus*, whereas *H. histrix* was recorded in the least number of fishing gears (Table 4). Trawling gears captured *H. histrix, H. kelloggi*, *H. spinosissimus*, and *H. trimaculatus* most frequently, whereas gillnets captured *H. kuda* was most frequently (Table 4). *H. kuda* had the greatest percentage of sampled catch under length at maturity (66%), whereas *H. histrix* had the smallest percentage (0) (Table 5). Gillnets caught the most immature *H. kuda* and *H. trimaculatus*, whereas trawls captured the most immature *H. kelloggi* and *H. spinosissimus* (Table 5). Only *H. trimaculatus* had a sex ratio statistically different than 1, while more females were captured than males ($X^2 = 5.8384$, d.f. $= 1$, p-value $= 0.01568$, Table 5). For additional analyses of catch under length at maturity and sex ratio by species by gear type, see Supplementary Material, Section 2.

Vulnerability analysis: which species is most at risk?

Our modified productivity and susceptibility analysis revealed that *H. kelloggi, H. kuda*, and *H. trimaculatus* are the three species most susceptible to Thai fisheries (Table 6). We identified *H. kelloggi* as the most susceptible to otter trawls, whereas *H. kuda* is the most susceptible to gillnets (Figure 2). *H. trimaculatus* is highly susceptible to two types of gears: otter trawls and gillnets (Figure 2). Purse-seines, pushnets, and small-scale cages exerted the least pressure on all three species, with susceptibility scores at low levels (1.2 for all three gears on all three species). Three species had the same level of productivity risk (high) regardless of how it was assigned: *H. histrix, H. kelloggi*, and *H. trimaculatus* (Supplementary Material, Section 1). A fourth species, *H. kuda*, also had the same level of productivity risk (moderate) when risk was assigned based on productivity attributes of only large bodied Southeast Asia seahorses (Supplementary Material, Section 1).

Discussion

Our research shows, with a Thai example, that both commercial and small-scale indiscriminate fisheries have large impacts on data-poor fishes. We estimated the mean annual catch of *Hippocampus* spp. in Thailand at 29 million individuals, more than threefold higher than previous estimates for Thailand (Foster *et al.*, 2016; Lawson *et al.*, 2017). Our research confirms

Table 3. Data summary of five port sampled seahorses from four commercial and two small-scale fishing gears in coastal Thailand.

	Gear type	No. fishers interviewed (*n*)	Fisher reported mean catch vessel^{-1} year^{-1} (95% CI)	Proportion fishers with positive catch	Fleet size	Estimated yearly mean total catch (95% CI)	Number of port-sampled seahorses	% sampled catch under length at maturity	Sex ratio (% male)
Commercial	Otter trawl	38	5 472 (1–11 446)	0.97	2 553	13 551 274 (2 476–28 346 024)	195	10.2	0.43
	Pair trawl	48	6 534 (1–14 055)	0.98	912	5 839 963 (894–12 562 406)	148	15.5	0.43
	Purse-seine	38	188 (1–401)	0.62	1 774	207 208 (1 100–440 861)	5	20.0	0.5
	Pushnet	10	106 (1–237)	0.6	1 233	78 419 (740–175 442)	2	0	0.5
Small-scale	Gillnet	260	411 (232–591)	0.7	30 952	8 911 451 (5 025 150–12 797 751)	146	47.2	0.51
	Cage	51	192 (17–366)	0.36	6 410	442 313 (39 898–844 727)	2	50.0	0.5
Total		**306**	---	**0.58**	**43 834**	**29 030 626 (5 070 258–55 167 211)**	**498**	**22.8**	**0.45**

the growing literature that small-scale fisheries exert fishing pressure greater than or equivalent to commercial gears (e.g. Peckham *et al.* 2007; Shester and Micheli, 2011). Our results identified three seahorse species particularly susceptible to fisheries in Thailand (*H. kelloggi*, *H. kuda*, and *H. trimaculatus)*, indicating that Thailand should focus its management efforts on the fisheries with the dominant catch of these species (commercial otter trawls and small-scale gillnets). The data-limited fishery assessment we employed enabled us to gain confidence in results from our simpler analyses and provided guidance to initiate a precautionary management plan, as found in other studies (Tuck *et al.*, 2011; Brown *et al.*, 2013). However, one critical drawback, as commonly cited with this method, was that we were unable to determine species-specific targets or reference points to ensure sustainable management (FAO, 2010; Tuck *et al.*, 2011). A current measure of stock status such as $\mathbf{B}/B_{\mathrm{msy}}$ or an index of relative abundance would have enabled us to place our results in the context of species target or reference points.

Our research confirms that commercial indiscriminate fisheries in Thailand catch large annual numbers of seahorses, which are just one of the many Thai non-target fish genera (Lymer *et al.*, 2010). Our annual estimates from the Thai otter trawl fleet (13.6 million seahorses year^{-1}) are much larger than previous otter trawl estimates in Thailand (ca. 2 million year^{-1}) (Perry *et al.*, 2010), most likely because our study had larger sample sizes. Indeed, the annual estimates from the commercial trawl fleet are also larger than estimated seahorse trade volumes from Thailand or any other country (Foster *et al.*, 2016). Our large annual catch estimates from Thailand call into question the latest global estimate of seahorse bycatch (37 million individuals) because our commercial estimates are larger than those for all of Thailand (ca. 9 million individuals) cited in that study (Lawson *et al.*, 2017). In our study, seahorses were not susceptible to all commercial gears. Despite documentation of the destructive nature of pushnets operating in coastal waters (Tokrisna *et al.*, 1997), we found that the annual capture of seahorses from pushnets was 51- to 61-fold lower in terms of catch rate and ca. half the fleet size of the commercial trawl fleets. We found the Thai purse-seine fleet had moderate catch rates and fleet size, despite the fact that bycatch from this gear type is not well recorded in the seahorse literature (Lawson *et al.*, 2017).

Small-scale fishing gears are typically considered benign compared to destructive fishing gears such as trawlers (Kaiser *et al.*, 2002), but our study supports research indicating that small-scale fisheries can have large impacts (Hawkins and Roberts, 2004; Shester and Micheli, 2011). Our study expands on research in Malaysia (Lawson *et al.*, 2015) documenting that seahorses are indiscriminately captured from small-scale gears, with annual estimates on par with commercial gears such as pair trawlers. Small-scale fishers in Thailand have fourfold more registered fishing boats than the commercial fleet (DoF, 2015), an attribute which led to annual seahorse catch estimates to be equivalent or greater than some commercial gears. Such results are similar to the pressures exerted on sea turtles by small-scale fishers in Mexico, where catches per trip were low at the individual level, but the vast number of participants in small-scale fisheries lead to large annual catches (Peckham *et al.*, 2007). Official catch statistics in Thailand, as in many countries, often underreport small-scale fisheries catches and fail to include small-scale gears in management plans (Teh *et al.*, 2015). The large number of small-scale catches in our study, along with previously documented

Table 4. Port sampling results from 2013 and 2014 for seahorses (number of individuals) by species by gear type from commercial and small-scale fisheries in Thailand.

	Commercial				Small-scale		
Species	Otter trawl	Pair trawl	Purse-seine	Pushnet	Gillnet	Cage	Total
H.histrix	0	2	0	0	0	0	**2**
H.kelloggi	38	27	0	0	2	0	**67**
H.kuda	2	1	0	1	67	0	**71**
H.spinosissimus	38	41	1	0	15	2	**97**
H.trimaculatus	117	77	4	1	62	0	**261**
Total	**195**	**148**	**5**	**2**	**146**	**2**	**498**

Table 5. Percent of Thai commercial and small-scale fisheries port sampled catch under length at maturity, and sex ratios, by seahorse species.

Species	% sampled catch under length at maturity	Sex ratio
H.histrix	0	0.5
H.kelloggi	28.3	0.43
H.kuda	66.1	0.56
H.spinosissimus	18.5	0.48
H.trimaculatus	11.4	0.41

perceptions and motivations of small-scale fishers in Thailand, highlight that the inclusion of small-scale fishers is critical for successful fishery management(Lunn and Dearden, 2006; Panjarat and Bennett, 2012).

We found simple overfishing indicators (Rowe and Hutchings, 2003; Froese, 2004) useful to assess pressure from fishing gears. Our study found large proportions of juvenile seahorses in small-scale fishing gears, but not in commercial gears, suggesting that small-scale gears are less selective than their commercial counterparts for juvenile and immature fishes (Watson *et al.*, 2006; Foster and Vincent, 2010). One explanation for this divergence may be that small-scale fishing gears in Thailand tend to fish in coastal waters that act as habitat for young fishes, whereas commercial gears fish farther from shore (Lymer *et al.*, 2010). Our second overfishing indicator, sex bias, did not identify any particular gear type at risk for overfishing, but was useful at the species level, as seen in Malaysia (Lawson *et al.*, 2015). Similar to our study, sex ratios of *H. trimaculatus* catches in the southwest region of Peninsular Malaysia were female-biased (Lawson *et al.*, 2015). However, other studies of exploited seahorses found male-biased ratios (Baum *et al.*, 2003), and it was hypothesized that pregnant males may be more susceptible to capture because they are less likely to expend energy avoiding fishing gears (Baum *et al.*, 2003). For seahorses, a bias in sex ratio, whether for males or females, is equally undesirable because seahorses form pair bonds and are monogamous through the breeding season (Foster and Vincent, 2004). Therefore, losing a mate to fishing pressure may alter the reproductive success of these fishes (Foster and Vincent, 2004).

Our research confirms that there is value to modifying vulnerability analyses to match available data (Braccini *et al.*, 2006; Tuck *et al.*, 2011). Our results modified the classic first paper on productivity and susceptibility analysis by drawing on the attributes available for our fishes related to productivity and then creating our own susceptibility attributes based on available fishery data (Stobutzki *et al.*, 2001). Species-specific modifications made to vulnerability analyses such as ours have been deemed successful for other groups of species such as seabirds and marine mammals (Tuck *et al.*, 2011; Brown *et al.*, 2013). The procedure we used to generate data for the productivity-susceptibility analysis, i.e. using life history characteristics from FishBase (2016) and data from several months of interviews and port sampling, could easily be replicated for other groups of fishes where more sophisticated data are lacking. This suggests vulnerability analysis may be an acceptable compromise between data-rich fishery stock assessments and extrapolation from sister groups of species (Honey *et al.*, 2010).

There are three key limitations to our research. First, there is a large amount of variation in our annual catch estimate for Thailand. However, large levels of variation have been documented in annual catch estimates for other stocks where abundance is estimated in billions (Hill *et al.*, 2012). Second, using a high proportion of immature individuals as an indicator of high risk of overfishing is only appropriate when fishing mortality is high and adults are vulnerable to fishing (Cope and Punt, 2009). Although we do not know the specific fishing mortality for any of the fisheries on seahorses in Thailand, both small-scale and commercial Thai fisheries have documented effort beyond that required to achieve maximum sustainable yield for numerous target species (Pomeroy, 2012). Previous research has documented adult seahorse capture in multiple fishing gears, indicating that adults are susceptible to fishing (Baum *et al.*, 2003; Lawson *et al.*, 2015). Third, our results from the vulnerability analysis hinge on the appropriateness and accuracy of the life history parameters obtained from Fishbase, which have been shown to have bias for more “conventional” species (Thorson *et al.*, 2014). However, previous research has identified that seahorses conform to some of the life history relationships used to calculate these parameters (Foster and Vincent, 2004), and we sought to include regionally appropriate values when available (Lawson *et al.*, 2015).

In the spirit of adaptive management (Walters and Holling, 1990), our results indicate the value of focusing on commercial trawl and small-scale gillnet gears in Thailand since they captured the greatest numbers and exerted pressure on the most vulnerable species (*H. kelloggi*, *H. kuda*, and *H. trimaculatus)*. Incidentally, *H. histrix* and *H. spinosissimus* would benefit from management measures aimed at trawling gears, even though these species scored the lowest in terms of susceptibility from fishing. Given that spatial management is one of the best options for trawl fisheries management, the issue for Thailand will be their enforcement because Thailand already has spatial management measures

Table 6. Productivity and susceptibility scores and their associated risk for five Thai seahorse species.

Species	Productivity	Risk: productivity	Susceptibility to fishing	Risk: susceptibility to fishing	Overall risk
H. histrix	2.00	High	1.00	Low	Low
H. kelloggi	1.69	Moderate	1.34	Low	Moderate
H. kuda	2.15	High	1.67	Moderate	High
H. spinosissimus	1.65	Moderate	1.00	Low	Low
H. trimaculatus	2.31	High	2.34	High	High

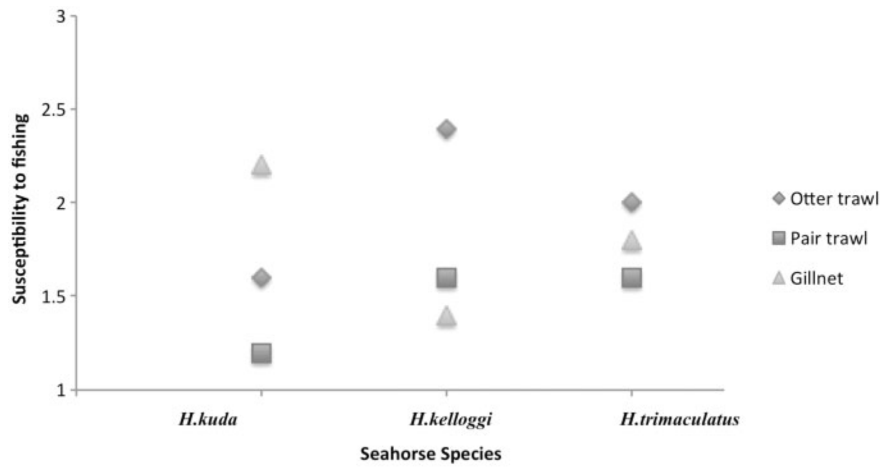

Figure 2. Susceptibility to three Thai fishing gears for the three seahorse species with greatest productivity risk, *H. kuda, H. kelloggi,* and *H. trimaculatus*.

(e.g. marine national parks, no trawl zones) in place (CITES, 2013). Thailand can begin to evaluate the effectiveness of current management measures with the knowledge provided by this research and draft a precautionary management plan to assist with sustainable management of national fisheries while also meeting international CITES recommendations (Walters and Holling, 1990; CITES, 2012).

As found in our study, both small-scale and large-scale fisheries can have significant impacts on fish populations (Shester and Micheli, 2011). Resource managers need flexible tools to initiate sustainable management plans for both small and large-scale fisheries as well as for target and non-target species (Honey *et al*., 2010). Creative solutions that use available or easy-to-generate data should be considered in all contexts, because with continued marine species declines, we cannot afford to wait for better data (Johannes, 1998). Such solutions are not easy to identify or implement given the challenges of data-limited fisheries, indiscriminate fisheries, and new markets increasing demand for all species captured by fishing gears (Honey *et al*., 2010; FAO, 2012). The path forward to sustainable fisheries may lay in simple assessments like vulnerability analyses that support the development of precautionary management plans while longer-term data are collected.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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