A Bargain for Tuna

Market Based Solutions to Bigeye Tuna Bycatch

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1 Summary

Bigeye tuna in the Western Central Pacific are an economically and ecologically important species that is experiencing intense overfishing. Regulatory solutions that have proven successful for other tuna species have been failed to prevent bigeye overexploitation. Bigeye are targeted for the lucrative sashimi market. However, overfishing of bigeye stems in part from accidental catch of juvenile bigeye in the massive skipjack tuna fishery, creating a mismatch in incentives that perpetuates the overfishing of bigeye. Countries such as Japan and Indonesia, that engage in the substantially in the targeted bigeye fishery, stand to benefit from fishery reforms, while skipjack targeting countries such as the United States of America and Spain bear the costs. Here we show that conditions exist under which bigeye beneficiaries could make payments to countries that bear the costs of those benefits, and in doing so generate economic and ecological improvements for both parties. Many environmental problems, from tuna to climate, persist despite the presence of proven solutions. Our results explore the potential of Coaseian bargaining to overcome the this class of persistent problem, through the lens of ending bigeye tuna overfishing.

2 Bigeye Background

At their face the presence of many environmental problems, from overfishing to climate change, seem natural. Hardin (1968) predicted that common pool resources such as the air and the seas are inherently doomed without strong regulatory restraint. And yet, we have in fact seen a great number of environmental successes. We have slowed deforestation, improved air quality, and reached historic climate agreements. The critical question then is why do some environmental problems persist despite the presence of demonstrated solutions?

Tunas, often presented as the canonical example of tragedy of the commons, are also a perfect example of this conundrum. As a highly migratory species, they spend much of their life cycle in the high seas or crossing through different countries' exclusive economic zones (EEZs). As such, they appear to be ready-made for a tragedy of the commons. Recent studies on the state of global tunas show a counter-intuitive result though: the majority of global tuna stocks are being managed at near target biological levels (Pons *et al.* 2016). However, some tuna stocks, notably those of bluefin and bigeye tuna, have failed to achieve necessary reductions in fishing mortality rates. Why then have some tuna stocks managed to overcome the common-pool challenges presented by highly migratory stocks, while others have not? We propose that market dynamics help explain this discrepancy, and suggest that market solutions may provide a path forwards for this and other persistent environmental challenges.The interesting question becomes then not how do we manage tunas, but why are some tuna stocks successfully managed while others fail? In analyzing this question, we can better understand why some environmental problems persist, and in doing so propose a novel market solution to these challenges. We illustrate this concept using the persistent overfishing over the Bigeye tuna (*Thunnus obesus*) stock in the WCPO.

Many environmental problems such as this persist, despite general agreement that solutions are necessary. More decentralized approaches to addressing the problem of over-access of common pool resources offer attractions by potentially narrowing the scope of the problem and enlisting user incentives. Ronald Coase (1960), winner of the 1991 Nobel prize in economics, envisioned a trading process, by which potential beneficiaries would pay those who would bear the costs of access and use constraints. The key issues are whether or not there is sufficient surplus, so that a willingness to pay from beneficiaries > the willingness to accept from the parties that incur costs, and whether or not the transaction costs of such exchange are low enough to facilitate a Coaseian bargain. Lowering transaction costs includes reducing the range of the problem potentially and thereby limiting the number of bargaining parties and lowering enforcement costs. We demonstrate the potential for such a Coaseian bargain for reducing the overfishing of bigeye tuna in the WCPO.

2.1 Proposed Solution

We hypothesize that bigeye overfishing is largely due to a mismatch in market incentives. Management decision reached by the WCPFMC require agreement between member states. States with heavy vested interests in the skipjack purse-seine fishery are likely to resist measures that reduce their catches for the benefit of member states that predominately engaged in targeted bigeye fishing. We propose a Coaseian solution to this problem, through a "beneficiary pays" system. Skipjack purse-seiners must currently purchase fishing days from the Parties to Nauru Agreement (PNA) countries in order to fish in the waters controlled by the PNA member states. Under our proposed market, bigeye interests would subsidize the purchase of fishing days by skipjack vessels, so long as fish-aggregating devices (FAD)s are not used in those purchased days. FADS increase the catch rates of both skipjack and juvenile bigeye. The willingness to pay of the bigeye fishermen depends on the expected increases in targeted bigeye catch that reductions in juvenile bigeye bycatch could produce. The willingness to accept of the skipjack fleet depends on the expected costs in lost skipjack catch from agreeing not to use a FAD on a given fishing day.

2.2 The WCPO Bigeye Tuna Fishery

Bigeye tuna are a highly valued species that live in open waters of tropical and temperate oceans around the globe. Bigeye roam the oceans feeding on fish, cephalopods and crustaceans (Bertrand *et al.* 2002). They grow to over 2 meters in length, reaching sexual maturity within 2-3 years as they reach sizes of 1 meter (Schaefer *et al.* 2005). They spawn year-round with peaks from February to September throughout the oceans (Sun *et al.* 2006).

40% of bigeye tuna caught throughout the planet comes from the Western Central Pacific Ocean (WCPO), totaling approximately 160,000 tons per year(**???**; FAO 2014). Tuna in this region are managed by the Western and Central Pacific Fisheries Commission (WCPFC), a collection of countries that collectively reach agreements on the management of tuna stocks fished in the WCPO. The most recent assessment of the bigeye population in the WCPO indicates that the stock is being overexploited. Current fishing levels would be expected to reduce the bigeye population by over 50% in the coming years (Harley *et al.* 2014).

Bigeye caught in the WCPO are primarily targeted by two distinct fisheries. Adult bigeye caught by pole-and-line and long line make up approximately 50% of annual captured volume (**???**). These line-caught Bigeye tuna are primarily sold in the lucrative Asian sashimi market, reaching prices up to $10/kg (**???**). However, the other 50% of bigeye caught each year come from accidental catch (bycatch) of juvenile bigeye in the massive WCPO fishery for skipjack tuna (*Katsuwonus pelamis*). The WCPO skipjack fishery is pursued by a fleet of purse-seiners, often utilizing fish-aggregating devices (FADS). This fishery deploys FADs such as floating buoys to attract large schools of skipjack, and then uses a large encircling net to pull in the fish. The WCPO skipjack fishery catches over 1.9 million tons per year (Sumaila *et al.* 2014), most of which is sold to the canning industry for $1/kg(**???**).

Juvenile bigeye aggregate with skipjack schools near FADs. Due to the relatively indiscriminate nature of seining, these juvenile bigeye are then captured along with the targeted skipjack tuna. Juvenile bigeye bycatch makes up only ~3-4% (**???**) of the landed volume from the skipjack purse-seine fishery, but do to the massive size of the skipjack industry, this amounts to nearly 50% of all the bigeye captured in the WCPO. In addition, the bulk of these bycatch bigeye are juveniles, meaning that they have not had an opportunity to reproduce and contribute to the population.

The bycatch of bigeye in the skipjack fishery is the key to understanding the persistent overfishing of this important stock. Bigeye are targeted by well over 20 major fishing nations across many more exclusive economic zones (EEZs), yet other tuna stocks face similar problems and have been successfully managed through regulatory mechanisms such as catch limits (Pons *et al.* 2016). The overfishing of bigeye presents a problem in incentives: the benefits of reducing bigeye overfishing primarily captured by countries such as Indonesia and Japan that catch and consume a large amount of the targeted bigeye catch, while the costs of reducing bigeye bycatch are borne by skipjack fishing interests such as the United States and Spain.

2.3 Institutional Structure

Twenty four states and territories are found in the Western and Central Pacific ocean (WCPO). The majority of ocean area and fishery landings (80-90%) in the WCPO falls within the EEZ's of Pacific Island States (the rest is landed in the high seas(ICUN 2008)).Since 1997, 34 flag states have reported tuna landings in the WCPO (Sumaila *et al.* 2014). Ten percent of bigeye catch from purse seine vessel occurs in the high seas, the remainder is from the EEZs within the WCPO (**???**). Between 9 and 15 vessels are responsible for over 25% of the bigeye bycatch from the WCPO (**???**)

Two primary management institutions operate in the WCPO: WCPFC and FFA. In 1979, the Forum Fisheries Agency (FFA) was established and includes 17 member countries.The purpose of the FFA is to help align national fisheries management policies, coordinate surveillance and enforcement, and assist with collective bargaining with distant-water fleets. Each member state/country is represented by one member in the FFA and decisions are based on consensus, or two-thirds majority.

In 1982, the enactment of the The Nauru Agreement was coordinated by the FFA. The Nauru Agreement is a subregional agreement between 8 Pacific Island States, collectively known as PNA members, that control 25-30% of the global tuna supply, and 60% of the western and central Pacific tuna supply. The eight signatory members of PNA are: Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands, and Tuvalu.

Three Implementing Arrangements have been established under the Nauru agreement that all PNA members agree and adhere to regarding purse seine fishing in their EEZs through management measures or licensing requirements. The first arrangement developed a regional register for foreign fishing vessels, which was adopted by the FFA in 1988 and was followed by the development of a Vessel Monitoring System that requires all vessels have a ALC. The Second Arrangement prohibited transshipment at sea, implemented high seas catch reporting and maintenance of log books, and allowed for placement of observers on request by licensing party. The Third Implementing Arrangement closed fishing in high seas to vessels licensed to fish in PNA waters, established an annual three month FAD closure, and implemented a requirement that all catch be retained (with a few exceptions). In 1992, The Palau Arrangement was signed by PNA members (excluding Tuvalue) and went into force in 1995 (Dunn *et al.* 26 February - 2 March 200626 February - 2 March 2006). This agreement set a vessel limit for the number of purse seine vessels licensed to fish in member's EEZs, which later was replaced by the Vessel Day Scheme.

The WCPFC was established in 2004 and is an international fisheries body that seeks to ensure, through effective management, the long-term conservation and sustainable use of highly migratory fish stock. Membership to the commission is open to any States that participated in the negotiating of the 2004 convention. The WCPFC has 26* members that include both local and foreign flags., 7 participating territories, and 7 cooperating non-members. FFA requires: ALC always on to report to the regional VMS, minimum data reporting standards and a requirement for regional vessel registration.

The Nauru Agreement is a subregional cooperation and management agreement between 8 Pacific Island states in the WCPO that collectively account for 25-30% of the world's tuna supply. PNA agreements include: providing annual access to all PNA EEZs by purse seine vessels, an agreement on the number of purse seine vessels allowed to operate in PNA waters, this has since been replaced by the vessel days management scheme. In 2010 PNA members prohibited purse seine fishing in Pacific Ocean high seas for by vessels licensed to fish in their combined EEZs. They also have established a ban on fishing near FADs from July-Septs, and require 100% observer coverage,minimum mesh size, and a requirement for retention of all catch. PNA countries have also adopted a MSC implementation plan to certify free-school skipjack purse-seine fishery. They are currently set to develop a FAD registration that will be trialled in 2016.

2.4 Vessel Day Scheme

In 1992, under the Palau Arrangement for the Management of the Western Pacific Purse Seine Fishery, PNA members implemented a limit to the number of purse seine vessels that could be licensed to fish in their respective EEZs to limit total effort in the fishery. The initial limit for purse seine vessels was capped at 164, and increased to 205 in 1994 (Dunn *et al.* 26 February - 2 March 200626 February - 2 March 2006). Under the vessel limit, access fees charged by PNA members were ~5-6% of total catch value, vessel capacity increased, and exemptions allowed for the entry of additional domestic vessels (Havice 2013). During the late 1990s, as purse seine tuna landings continued to increase, interest from new participants in joining the lucrative purse seine fishery grew, and concerns about the status of bigeye and yellowfin stocks were raised(Tamate 2013).

In 1999, a review of the Palau Arrangement vessel limit concluded that limiting the number of fishing days as a management mechanism (instead of vessels) would increase the PNA members control and flexibility over who could fish in their waters (Tamate 2013). The Vessel Day Scheme (VDS) was adopted in 2000, and became effective in December 2007 after PNA members were assured that the allocation of effort days would not undermine their desire to expand their domestic fleets, and that socio-economic factors would be weighed when determining total allocated effort (TAE)(Tamate 2013). The VDS applies to all EEZ waters of PNA member countries, excluding the archipelagic waters of PNG and the Solomon Islands. International waters were strategically excluded from the VDS by PNA members to exclude Distant Water Foreign National Fleets

(DWFN) from having input in the development of the new management scheme (Hanich and Ota 2013). An effort management scheme was chosen over a quota scheme because of the lower associated monitoring costs and more realistic enforcement capabilities (Aqorau 2009).

The objectives of the VDS were to limit fishing effort, and to maximize the economic returns and control of PNA EEZ waters by PNA member countries (Tamate 2013). Under the VDS a total allocated effort is established (TAE) in terms of total number of fishing days. Members are permitted to buy and sell unused days from each other, but following a 2010 amendment, are not permitted to trade days across management years (Hanich and Ota 2013). The original VDS scheme defined a fishing day "as any calendar day, or part of the calendar day, during which a purse seine vessel is in the EEZ of a Party outside of port, and not reported as a non-fishing day". The definition of fishing days in the VDS varies by vessel size. One calendar day is equal to 0.5 fishing days under the VDS scheme for vessels <50m, fishing days and calendar days are equal for vessels between 50 and 80 m, and for vessels >80m one calendar day is equivalent to 1.5 fishing days (Hanich and Ota 2013).

From 2007-2010 TAEs were set based on 2004 fishing effort levels (**???**), and from 2011 forward based on 2010 effort levels (**???**). Party allocated effort (PAE), the total number of days allocated to each PNA country, are then allocated across the PNA member countries based on a combination of: 1. the EEZ's historical fishing effort levels, and 2. estimated relative tuna biomass within each EEZs.(Yeeting *et al.* 2016). In addition to PAEs,days are allocated to vessels operating under the FSM arrangement, and days were under the U.S. Treaty Agreement(Tamate 2013).

From 2007 to 2010, the TAE increased from 33,856 to 44,703 fishing day, and the total PAE allocation was 28,468 and 33,798 fishing days for each year, respectively. The majority (>70%) of the PAE has historically been allocated between PNG, FSM, and Kiribati (Havice 2013). A fixed cap of 3,907 fishing days each year is allocated to vessels operating under the FSM. This was established to avoid a potential loophole in the VDS scheme (Aqorau 2009). Although fishing days are accounted vessels fishing under the U.S. Treaty and subtracted from the TAE, because the Treaty was established before CMM2005-01, these vessels were exempt from maintaining 2004 effort levels, and instead have only been restricted by a 40 vessel limit cap (Hanich and Ota 2013). This exemption for vessels operating under the U.S. Treaty was a large contributing factor for the purse seine fishery exceeding 2004 fishing effort levels over this time period (Tamate 2013).

In 2007 revenues generated through VDS access fees were valued at $US 77 million (Havice 2013). Additionally, the U.S. Treaty, which allowed unlimited access of 40 U.S. flagged vessels to fish in PNA waters was valued at 21 million a year. Three factors contributed to an increase in revenues generated through access fees over the next several years: 1. In 2010, under the Third Implementing Arrangement, the high seas were closed to vessels licensed to fish in PNA waters, 2. In 2011, a minimum benchmark of $5,000 was set as the price per fishing day to reduce competition between PNA members, which often resulted in lowering fishing day price (Yeeting *et al.* 2016). By 2013,revenue generated through access fees was estimated to be $US 494 million(Havice 2013). In 2014, the minimum benchmark fishing day price was increased to $6000, and for 2015-16 was set at $8000(Yeeting *et al.* 2016).Countries commonly negotiate access fees higher then the minimum benchmark, though data on these prices are not available, a renegotiation of the U.S. Treaty in 2013 included purchasing of 8000 fishing days for $US 63 million for an average price of US$7800 (Havice 2013).

While the VDS scheme has been successful at reaching economic objectives of PNA member countries by increasing access revenues from 5-6% of total catch value (under the vessel limit) to 14% of total catch value, it has been widely criticized as failing to meet conservation and management objectives (**???**; Tamate 2013). Under the VDS scheme, the number and capacity of purse seine vessels in the region has increased, a steady increase in the TAE from 33,856 days in 2007 to 45,000 days in 2016 has occurred. Lack of a clear and consistent definition of 'fishing day' vs. 'non fishing day' is also attributed to undermining the VDS schemes effectiveness (Yeeting *et al.* 2016). In 2012, although not a PNA member country, Tokelau joined the VDS and was allocated 1,000 fishing days. The number of days far exceeds Tokelau's historical effort levels, meaning it likely won't be able to sell all of it's allocated days (Havice 2013). Fishing days unused by Tokelau can can be sold to other countries, creating an additional way for Tokelau to earn revenue. This will likely generate interest for other countries in the area to join the VDS as a way to earn revenue, and could lead to a further increase in the region's fishing effort (Havice 2013).

Currently, the FFA VMS system is used to monitor the number of days vessels operate in each EEZ, and the VDS has increased the quality of data in the purse seine fishery (Havice 2013). If a party exceeds its allocated days by less than 100 days, the number of days exceeded is deducted from the allocated days for the following year. If a party exceeds it's allocation by over 100 days, the deduction of days the following year is 120% of the excess (**???**).

(**still need to add a paragraph (or modify existing) to better summarize the pros/cons of vds and look into it's current (or potential) use in the long-line fishery)

2.5 History of Concern for Bigeye and Bluefin

The first formal assessment of the WCPO bigeye tuna stock in 2003 confirmed concerns that the population was experiencing overfishing (**???**). Since that time, the WCPFC has adopted a number of Conservation and Management Measures (CMMs) for bigeye tuna, but overfishing has continued and the stock is now overfished (**???**) (Table 1). The failure of the WCPFC to act collectively and take effective action to reduce fishing mortality (F) can be attributed to :1.Uncertainty on the status of the stock and disagreement on the need to take action, and 2. Disagreement between Members on who should bear the costs of taking action to reduce F and who will receive the benefits.

Of the 14 States that control almost all WCPO fisheries that impact bigeye tuna, six are Coastal States that receive benefits from the purse seine fishery through bilateral access agreements, and their own domestic fleets (**???**). The long-line fishery is dominated by DWFN fishing primarily in the high seas (**???**)…..

*will condesnse and add some examples of CMMS that have failed due to management burden issues and examples of disagreement on needed action (current draft is too long and needs a little reorginzation).

*(Should more detail be added to the above section? Do we want to include all the info on the full history of management in the WCPFC and why it has failed here?)

Intense fishing pressures on the Atlantic bluefin tuna populations began in the early 1960s, but it was not until 1998 that the International Commission for the Conservation of Atlantic Tunas (ICCAT) implemented its first rebuilding program for Western Atlantic bluefin (ICCAT, 2013). Catch limits for the eastern population have also been in place since 1998; however poor data collection prior to 2007 has constrained management decisions (ICCAT, 2015). In 2010, ICCAT established the Atlantic-wide Research Programme for bluefin tuna in an effort to improve the scientific advice provided to the Commission. Despite efforts to improve data collection, studies have shown high levels of mixing between the western and eastern populations which further complicates population estimates and likely leads to inflated numbers for the individual sub-populations (ICCAT, 2015). Throughout the 2000s, quotas for bluefin were set above scientifically recommended levels, and while stricter quotas have been implemented since 2010, little has been done to reduce the number of fishing vessels which has led to continued illegal fishing operations (GTC, 2014). Since the implementation of regulations in 1998, ICCAT has conducted 32 meetings and working group sessions regarding the Atlantic bluefin tuna fishery

2.6 FADs

FAD introduced in 1996 [Up until the mid-1990s, the majority of purse seine landings came from fishing 'free-school'(unassociated with FADs). Since that time catches have been almost equally split between FAD assocoiated and unassociated sets (Hare *et al.* 2015). Recently, consumer awareness has increased, resulting in an increasing number of sea food purchasers seeking 'free-school' caught tuna. Fishing on FAD decreases the number of sets where catch is zero or low, but increases the bycatch. Many types of FADs exist, but fall into one of two categories: drifting and anchored(Majkowski *et al.* 2007). Significant bigeye catch is commonly observed in the month following the end of the FAD closure(**???**). FADs believed to result in higher purse seine catches at a lower cost (**???**).FADs, seamounts, and reef edge areas substantially effect the catchability of bigeye tuna (Itano and Holland 2000). FADs accounted for 72.4% and 23.5% of all tag releases

Harley:“For example, closing a hot spot area with regards to total bigeye tuna catch would result in a 56 percent reduction in bigeye tuna catches, but also a 57% reduction in the total catch– saving 35,000 tons of bigeye tuna, but costing 800,000 tons of tuna”

2.7 Fleet Structure

The total number of purse seine vessels in the WCOP has increased from 180-200 between 1990-2006, to 280 in 2010, and 344 in 2014 (Hare *et al.* 2015). The five largest distant-water purse seine fleets operating in the WCPO are from Taiwan, Japan, Korea, the United States, and China. Together these five fleets made up 57% of the total WCPO ps tuna catch in 2013. The number of Taiwanese ps vessels has remained fairly constant due to limits imposed by the government, with 34 active vessels at the end of 2014. Japan had 40 active ps vessels in the WCPO in 2014, most of which are equipped with “ultra-low” temperature freezers on board. Japanese ps vessels recently started using helicopters to search for schools, a technique that has been used by Korean, Taiwanese, Chinese, and American fleets for many years. Korea’s ps fleet had 28 vessels and the United states fleet included 40 vessels in 2014. China distant-water ps fleet has grown from less than 20 vessels in 2009 to 69 in 2015. Ecuador, El Salvador, New Zealand, Spain, and Vietnam also have distant-water ps fleets operating in the WCPO, each catching 1-2% of the total ps tuna catch. Fleets from Indonesia and the Philippines caught 20% of the WCPO ps catch in 2013. The Philippines ps fleet included 40 vessels in 2009, though most vessels were older and less efficient than those in the other WCPO ps fleets. Data is not as readily available on the fleet size for Indonesia. The ps fleets of Papua New Guinea, the Solomon Islands, the Federated States of Micronesia, the Marshall Islands, Kiribati, Vanuatu, and Tuvalu were responsible for 23% of the WCPO ps catch in 2013. As of 2014, 51 vessels were flagged to PNG, 5 to the Solomon Islands, 10 to the Federated States of Micronesia, 10 to the Marshall Islands, 14 to Kiribati, 3 to Vanuatu, and 1 to Tuvalu(Virdin 2015).

More than 60% of all tuna catches in the WCPO occur within the EEZs of Kiribati and Papua New Guinea(Evans *et al.* 2015). In 2012, Kiribati sold or traded the most ps effort days (9479), followed by Papua New Guinea (9229), and the Federated States of Micronesia (5307) (Bell *et al.* 2015).

2.8 Market Structure

By and large, bigeye tuna catches from longline vessels are destined for the sashimi market, which mostly prefers the bigeye tuna for its greater fat content. Japan, Taiwan, China, and Korea contribute 63% of the total longline catch (~260,000 metric tons), 30% (~80,000 metric tons) of which is bigeye tuna (Macfadyen *et al.* 2016). The United States, Vietnam, Indonesia, Fiji, and Vanuatu are also notable longline countries, each bringing in over 10,000 metric tons of tuna annually. According to a recent study conducted by Poseidon Aquatic Resource Management Ltd., as of 2012 the ex-vessel value of bigeye caught by longline in the WCPO was estimated to be near US$680 million (Macfadyen *et al.* 2016). The unit price of bigeye sold on the Japanese sashimi market can range from US$5,000/mt to over US$10,000/mt, peaking between December and January when New Year celebrations in Japan drive up sashimi demand. The Japanese sashimi market accounts for 80% of global consumption of sashimi-grade tuna (Miyake *et al.* 2010). While Japan has the largest demand for sashimi and therefore a high interest in preserving bigeye tuna stocks, 80% of its sashimi-grade tuna is imported from Indonesia and Taiwan Province of China (XX Imported from these fishing countries (i.e flagged vessels) or from the waters of?). These suppliers should also be considered in potential Coaseian bargain solutions. **So loosely, the beneficiaries from a bigeye improvement would be Japan, Indonesia, and Taiwan. Indonesia and Philippines play a big role, but poor reporting**

The sashimi market system, as Miyake et al. (2010) puts it, “is one of the most traditional and complicated in the world”. After caught, a fish may exchange hands half a dozen times before reaching the consumer. In the WCPO, smaller longline fleets without ultra-low temperature (ULT) facilities tend to land their catches at local ports while larger longline vessels that fish in more distant waters typically transship their catches at sea. The traditional sashimi trade structure involves selling the catch at a landing port market or sending it to a central market for auction. Wholesalers that purchase the fish at market auctions then sell it to retailers or restaurants. However, there has been a trend in recent years for a single dealer to buy an entire catch straight from a vessel and then sell directly to large retailers, eliminating intermediate steps in the supply chain and reducing costs (Miyake *et al.* 2010). This consolidation of the supply chain not only develops economies of scale that can absorb the risks associated with fluctuations in the sashimi market but may also be integral to reducing transaction costs between bigeye longline interests and purse seiners; it would be easier to develop a solution from one large-scale sashimi trader than many different wholesalers.

Purse seiners in the WCPO dominate total catch volumes, bringing in more tuna than all other methods combined (Macfadyen *et al.* 2016). Korea, the United States, Papua New Guinea, Japan, and Taiwan are the leading purse seining nations in the region, together contributing over half of the total purse seine catch by weight. Skipjack tuna makes up the bulk of the species caught and is the primary fish used in the canning industry. In terms of processing and exporting, Thailand has been dominating the global canning industry in recent years, growing its share of WCPO canned tuna production from about 24% in 2008 to about 35% in 2012 (Miyake *et al.* 2010; Macfadyen *et al.* 2016). The value of skipjack caught by purse seiners in the WCPO has been estimated to be over US$2 billion as of 2012. Adding in the value of other fish caught by purse seines, including bigeye tuna, pacific bluefin tuna, and yellowfin tuna, this value goes up to about US$3.5 billion (Macfadyen *et al.* 2016). The unit price for purse seine fish sold to the canned tuna market is around $2,000/mt. It should be noted that around 20% of the bigeye tuna (larger fish) caught by purse seiners will be pulled from the catch and sold as low-grade sashimi where it will fetch a higher value than canned tuna. The remaining 80% is sent to be canned with the rest of the catch.

As for the bulk of purse seine landings destined for the canned tuna market, catches are either transshipped to foreign canning facilities, loined locally and then sent to an outside cannery, or canned within the region. Retail sales of canned tuna is controlled primarily by supermarkets that often own or finance the purse seine fleets, buy the catch at a pre-determined rate and then sell the canned product under their own "private" label. Trading of tuna from the WCPO is dominated by Tri Marine, Itochu, and FCF Fishery Co. Ltd.

It has been suggested that there may be a price premium associated with purse seine catches from free schools or natural FADs as opposed to artificial FADs (drifting or anchored) (Macfadyen *et al.* 2016). Though data on FAD use by individual vessels is extremely limited, some countries like Korea, Taiwan, Japan, Vanuatu, China and the Philippines have demonstrated a relatively low dependence on deployed FADs. This preference for free-school purse seine sets possibly indicates some added value to the fish size and species composition associated with those catches. Of the leading purse seine nations, the United States and Papua New Guinea are two that have large catches and a relatively higher dependence on artificial FADs.

3 The Coaseian Solution

The WCPFC requires consensus among member states to set regulations. This mismatch in incentives helps explain why bigeye continue to experience overfishing, despite the presence of clear scientific evidence of the unsustainability of current practices. Trans-boundary environmental problem such as tuna require international agreements. This by nature requires that countries blah blah blah. Why then not a regulatory solution for the bigeye? The regulatory solutions that have arisen through the WCPFMC are an outcome of the economic interests of the associated parties. That a similar regulatory solution has yet to resolve the challenges of bigeye bycatch is indicative that the participating nations do not perceive an economic incentive towards a regulatory solution.

Suppose though that a regulatory solution was adopted? Both the skipjack and bigeye tuna are well studied, with robust estimates of biomass levels and fishing mortality rates. Therefore, relative to many data limited fisheries, the question of what is required for the sustainable management of bigeye is not hampered by uncertain science. The reductions in bigeye catch needed to achieve levels of catch that would in theory produce maximum sustainable yield (MSY) are relatively well known. It is conceivable then that the some regulatory body could impose the required reductions in bycatch or targeted catch by the fishery.

Regulatory constraints that run contrary to economic incentives are often extremely costly. Keohane [-@]

estimated that the regulatory costs of acid rain controls (SO2) by 1990 were $135 billion annually in the US and the target reductions were not being met. Grafton et al. (2000) show that even under entry controls in the Pacific northwest halibut fishery in Canada, harvests doubled, vessel numbers were up by 40% and the fishing season had turned into a derby, with only 6 days in 1990. While regulatory controls can be effective at achieving biological goals, if they run contrary to economic incentives they may be costly to communities, and be plagued by poor enforcement.

We propose a novel solution, based around a beneficiary-pays solution. Rather than relying on regulation or taxation alone, Coase [@-Coase1960] suggests that given sufficiently strong property rights, if parties are allowed to negotiate an optimal allocation of benefits can be achieved if those that are willing to pay for reductions in an externality, such as overfishing, can make payments to those who would bear the costs for that reduction.

Could a Coaseian bargain for bigeye tuna in the WCPO be the solution to the persistent overfishing of stock? Specifically, does enough economic surplus exist such that bigeye fishing interests could pay skipjack fishing interests to reduce bigeye bycatch, and in doing so make both parties better off?

4 Methods

Our goal is to ask whether a Coaseian bargain might exist wherein the benefits to bigeye fishing interests of reduced bigeye bycatch are greater than or equal to the costs to the skipjack industry of achieving those bycatch reductions. Answering this question requires two general steps:

1. Estimate the changes in bigeye bycatch and skipjack catch resulting from removing FAD use
2. Estimate the stream of bigeye benefits and skipjack costs resulting from a given number of FAD days removed from the system.

4.1 Estimating the effect of FAD removal

The primary benefit of FAD use is to increase catch per unit effort (CPUE) of purse seine fishing, where effort is measured here in fishing day.One day of fishing with a FAD is more efficient than a day without a FAD, due both to decreased search time, and concentration of tuna around FADS (making the density of each pull higher). While this broad trend is clear, it is unclear from the literature exactly how much CPUE can be expected to change as a function of FAD use.

Our results require an estimate of the expected reduction in bigeye and skipjack CPUE as a result of FAD removal. We use an empirical approach to address this question, using data from the WCPFC of catch rates on and off FADs across space and time to fit a regression model of CPUE as a function of FAD use, along with other relevant covariates.

4.1.1 Data

The data utilized in this analyses are the location, timing, catch volumes, effort levels, and set numbers, provided by the WCPFC. Total catches on and off of FADs for skipjack and bigeye tuna are reported by the WCPFC at the resolution of year, month, latitude, longitude, and effort. This means that effort data are not directly separable for the catches on and off FADs. In order to get FAD specific CPUE, we utilize the proportion of sets on and off FADs at a given year, month, latitude, and longitude, where the effort associated with FAD catches is allocated in proportion to $\frac{sets_{FAD}}{sets_{No-FAD}+sets_{fad}}$. This is the same procedure followed by Harley *et al.* (2014). We also utilize sea surface temperature (SST) at the same resolution as the WCPFC data as an additional control. We also use the provided latitude and longitude data to identify the EEZ in which the particular country occurred. Together then, this provides us a database of 92524 observations of

CPUE for skipjack and bigeye tuna, along with each observation's associated fishing location, month, year, and SST.

We perform minimal data filtering before analysis. We utilize only data post 2007, in order to fit the model on data representing the "modern" regulatory structure of the industry. Catches from countries which never reported effort data (i.e. for which CPUE could not be calculated) were also removed. Locations at which less than 10 observations were available were also removed to improve the ability of the model to converge. The final dataset contains 9002 observations.

4.1.2 Model Structure

These data allow us to estimate FAD specific CPUEs, that give a rough sense that CPUEs on FADs are on average higher than CPUEs off FADs (Fig.1). However, we are left with a challenge here that we cannot be sure that differences in CPUEs on and off FADs may not be affected by other endogenous variables. For example, maybe purse seine vessels prefer to deploy FADs in areas that are naturally richer in bigeye tuna, inflating the perceived "FAD" effect on CPUE. Separating these effects properly would require an identification strategy, which will be pursued as an extension to this analysis. However as a starting condition, we utilize a regression based approach which assumes treatment ignorability of FAD use conditional on year, month, location of fishing, and SST at that observation. This particular model form was selected over other candidate models using leave-one-out cross validation (loo), which provides a measure of out-of-sample prediction accuracy.

Figure 1: Log-CPUE for skipjack and bigeye tuna on and off FADs. Small constants added to zero valuues to appear on plot

We fit the model using a Bayesian delta generalized linear model (GLM). The "delta" (also commonly known as a hurdle) model refers to the fact that CPUE is always greater than or equal to zero, fit using STAN through the `rstanarm` package in R (R Core Team 2016). Default uninformative priors were used. This delta priocess requires us to fit two separate models; one for the probability of catching anything (CPUE > 0), and a second that says conditional on catching anything, what is the expected CPUE. Both portions of the model use the same covariates. For observations for which CPUE > 0, we log transform the CPUEs and fit the logged CPUEs using a Gaussian distribution (as commonly done for CPUE data). The probability of CPUE being greater than 0 was fit using a binomial likelihood with a logit link. Using this model, then the expected CPUE for a given observation is given as

$$C\hat{P}UE = P(CPUE > 0)E(CPUE)$$

We fit this model separately for skipjack and bigeye tuna.

4.2 Calculation of Coaseian bargain.

Using this model, we can now estimate the CPUE as a function of FAD use, conditional on our other covariates. For each observation, we observe the "true" CPUE, given that observation's use of FAD, as well as the expected CPUE were that observation to use/not to use a FAD. To illustrate the process, consider only the observations in the database which utilized a FAD. We use our model to estimate the CPUE for species s at that observation were it not to use a FAD (using the mean estimated CPUE from the posterior predictive of that observation with FAD use set to FALSE). For that observation i then, we have the observed catch $C_{i,s,FAD}$ that was obtained for that observations effort E, and the expected catch without FAD use that would have occurred without the FAD ($C_{i,s,N\hat{o}-FAD} = CPUE_{i,s,No-\hat{F}AD} Effort_i$). We repeat this process each species, providing us with an estimate at each observation i of the bigeye and skipjack catch and CPUE with and without FADs.

For each observation i then, we calculate the reduction in bigeye tuna bycatch as

$$BycatchReduced_i = min(C_{i,bigeye,FAD}, (C_{i,bigeye,FAD} - C_{i,bigey\hat{e},No-FAD}))$$

and the amount of skipjack catch lost as

$$SkipjackLost_i = min(C_{i,skipjack,FAD}, C_{i,skipjack,FAD} - C_{i,skipjac\hat{k},No-FAD})$$

With this information in hand, we calculate the magnitude of the surplus available for a Coaseian bargain per number of FAD says bought n.

We first calculate the costs to the skipjack industry of removing n FAD days per

$$costs_n = \sum_{0:T}(p_{skipjack} SkipjackLost_n + p_{bigeye,seine} BycatchReduced_i)(1+r)^{-t}$$

Where NPV represents net present value, p is price for a given species, where price can be a function of gear, and r is the discount rate (set to 5%). This says that the costs paid to the skipjack industry represent the stream of revenues they would have expected to catch from selling skipjack and bigeye caught by purse seine vessels fishing on FADs if current conditions were to continue as they are forever. This assumption is reasonable as a starting evaluation, since skipjack tuna are abundant and not being overfished at the moment.

We calculate the benefits of removing n FAD-days to the bigeye industry dynamically, using

$$surplus_n = NPV_n - NPV_{n=0}$$

In other words, the bigeye benefits are represented by the increase in NPV from removing n FAD-days relative to the NPV they would expect under a business-as-usual (BAU) scenario.

4.3 Population Dynamics

We calculate the NPV of targeted bigeye catch generated by purchase of a given number of FAD days using a age structured population dynamics model with multiple fleets, allowing us to capture the effects both of changing the amount of bigeye tuna caught, and the size-structure of the tuna caught.

$$N_{t+1,a+1} = N_{t,a}e^{-(F_{t,a}+m_a)}$$

Where the total fishing mortality F at time t and age a is calcualted as

$$\sum_{g=1}^{G} f_{t,g}\delta_{a,g}$$

Where f denotes the fishing mortality of fleet g in time t, and δ is the selectivity at age of that particular gear.

Recruitment is defined throuhg a standard Beverton-Holt function, where

$$N_{t,a=1} = \frac{(\sum_a^A N_{t-1,a}W_aS_a)}{\alpha + \beta(\sum_a^A N_{t-1,a}W_aS_a)}$$

Where W is weight at age, S indicates the sexual maturity at age, and $alpha$ and $beta$ are defined per

$$\alpha = (SSB0/r0) * (1 - steepness)/(4 * steepness)$$

and

$$\beta = (5 * steepness - 1)/(4 * steepness * r0)$$

Where *SSB* is the spawning stock biomass under unfished conditions, *r0* are unfished recruits, and steepness is set to 0.8, per Harley *et al.* (2014)

Model parameters were taken from Harley *et al.* (2014) where possible. However, we estimated unfished equilibrium recruitment *r0* (and by extension *SSB0*), as well as the vector of ~600 $f_{g,t}$ values that explain the observed pattern of depletion and cathes presented by Harley *et al.* (2014). Model fitting was performed via maximum likelihood in Template Model Builder (TMB), through the general form

$$[r0, f, \sigma_c, \sigma_d|c, d] \propto normal(c|g(r0, f), \sigma_c)normal(d|g(r0, f), \sigma_d)$$

Where g represents the population dynamics process.

The purpose of this fitting step was to approximate the population dynamics estiamted by Harley *et al.* (2014), under the simplifying assumptions of our model.

Note that f and δ are indexed by fleet. This represents the fact that each of the three fleets modeled in this analysis (longline/pole and line (LL), purse seine (PS), FAD associated purse seine (PS-FAD)) has a different selectivity profile (Fig. 2). The LL fleet targets larger individuals, while the PS-FAD fleet captures younger (smaller) bigeye.

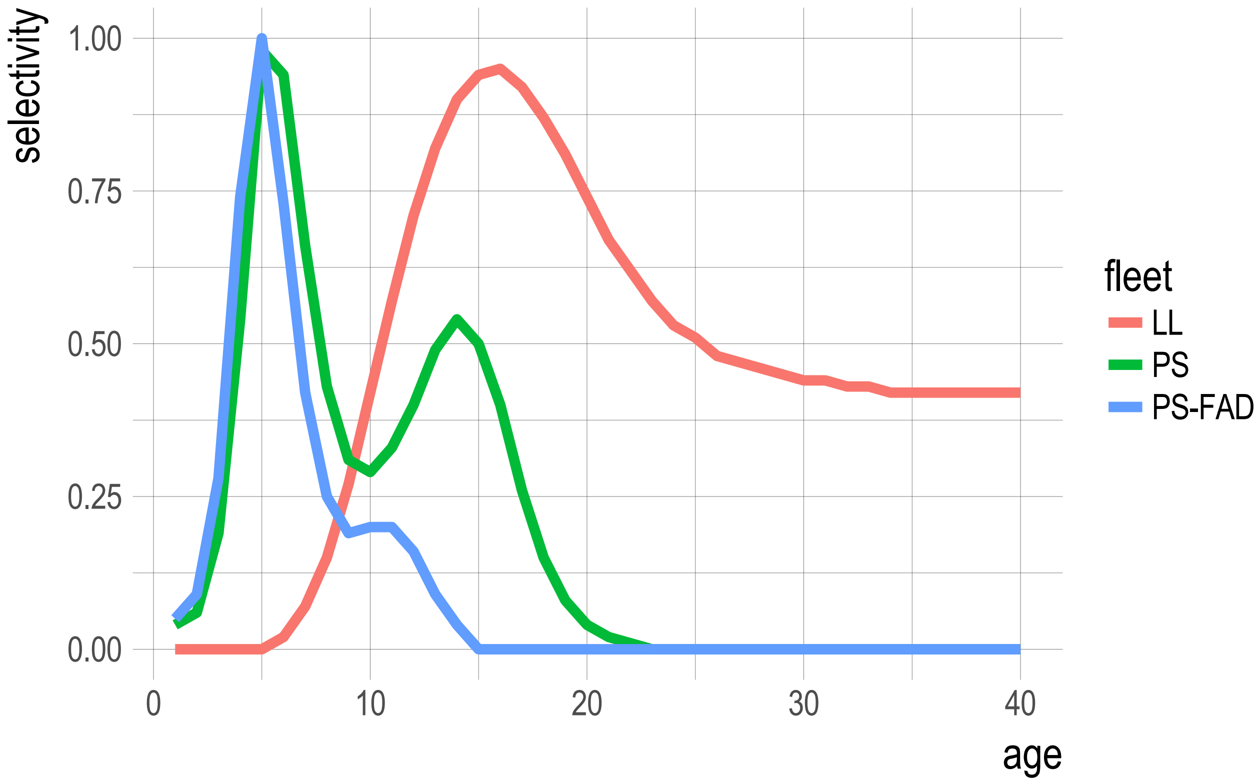

Figure 2: Selectivty at age by fleet for bigeye tuna

For a given number of FAD days removed, we used our regression framework to estimate the total reduction in bigeye bycatch. We then calculated the reduction in PS-FAD fishing mortality f that would have produced the new reduced amount of bigeye caught by the PS-FAD fleet, holding the f of the LL and PS fleets constant. We then projected the population forward in time, holding the new values of $f_{g,t}$ as constant. This constant f assumption allows catches to fluctuate with the changing size of the population, though of course we do not account for market-induced changes in the nature of f over time.

5 Results

5.1 Model Validation

Full regression diagnostics are available and will be presented as supplemental material. Posterior predictive diagnostics are promising. The mean and standard deviations estimated by the model are centered around the observed mean and standard deviations of CPUE in the data (Fig.3). We see though that the model on average overestimates both the maximum and minimum expected CPUE, but overestiamtes the minimum CPUE, likely due to the right-skew often introduced when log-transforming data (Fig.4. Further analyses may explore shifting towards a Gamma distribution to better represent the system.

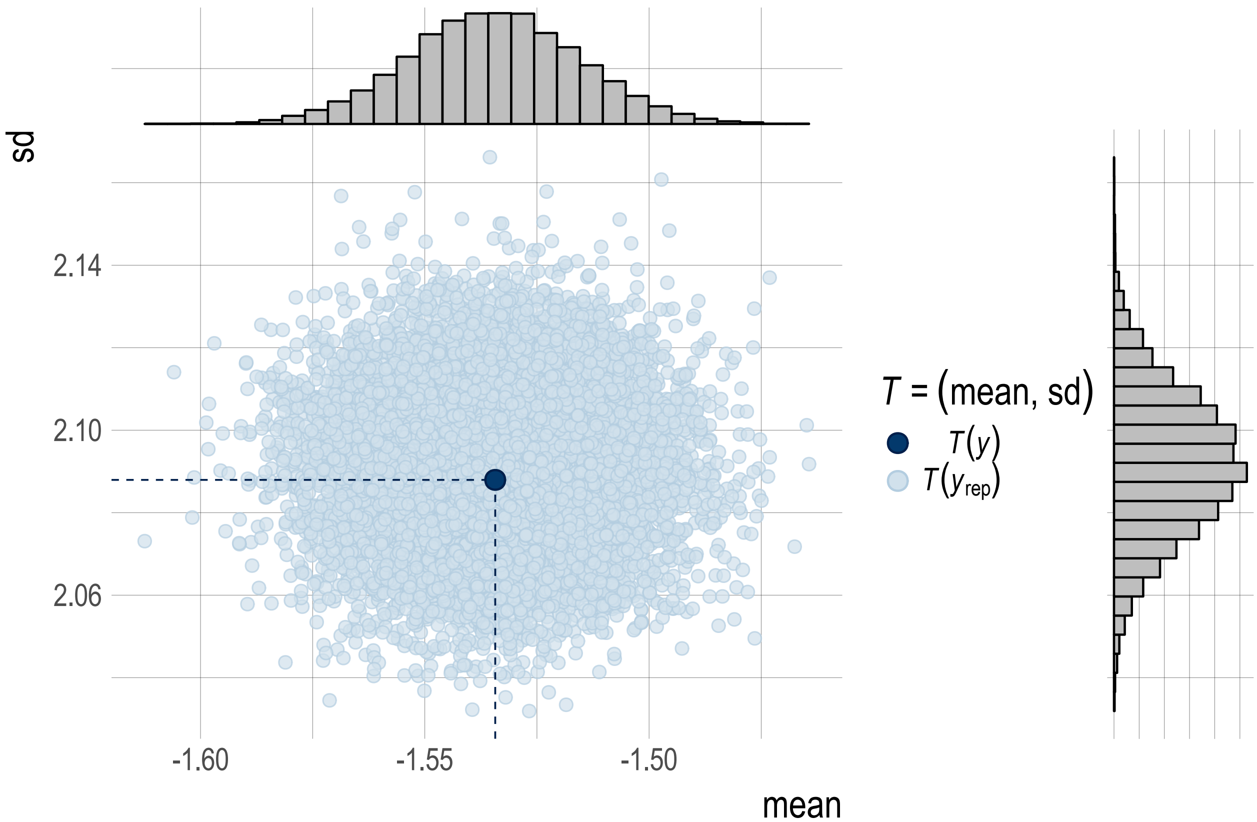

Figure 3: Posterior predictive draws of mean and SD of CPUE (black dots) comapred to observed mean and standard deviation of CPUE

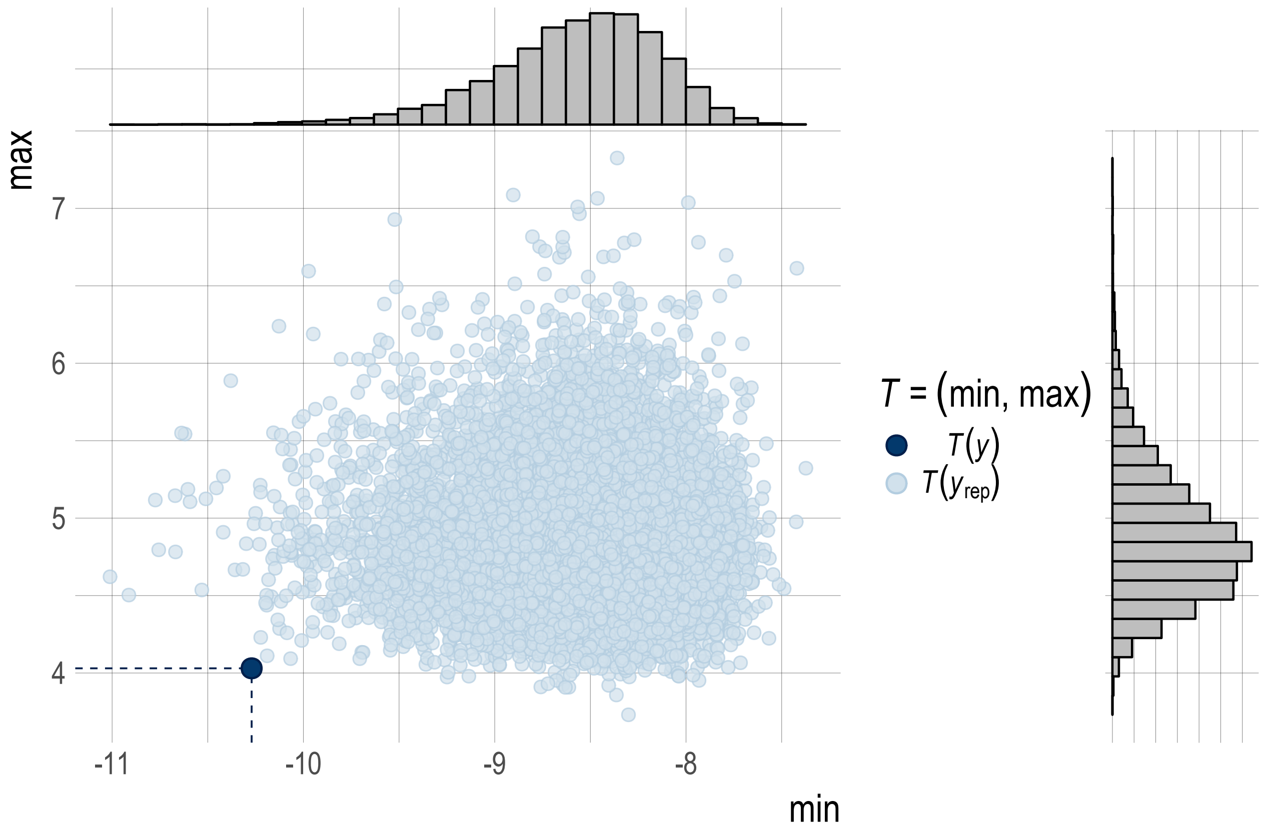

Figure 4: Posterior predictive draws of minimum and maximum CPUE (black dots) comapred to observed min and max of CPUE

Conditional on appropriate specification of the likelihoods, our true interest is whether our model can reliably predict changes in BET catches resulting from reductions in FAD days. As a test of the models ability to do this, we re-ran the model using only data prior to 2008. This is important, as the summer FAD closures began in 2008. These closures resulted in a dramatic reduction in the number of FAD days fished during the summer months, and a commensurate decrease in bigeye bycatch. This presents a somewhat natural experiment in the effects of dramatic reductions in FAD use on BET catches. We would like to know whether our model, fit to data outside this period, accurately predicts the total bigeye bycatch in the post-2008 period, including in the summer FAD-closure months.

We see that our model performs very well at predicting the levels of bigeye bycatch out of sample, including in the summer months during which the number of FAD days decreases dramatically (Fig.5). As a test of whether this relationship could perhaps simply be due to other covariates such as SST, we performed the analysis omitting FAD use as a covariate in the model. Without inclusion of FAD as a variable, the model was completely unable to reproduce the observed levels of bigeye bycatch out-of-sample, indicating that the FAD effect is likely driving force behind our results.

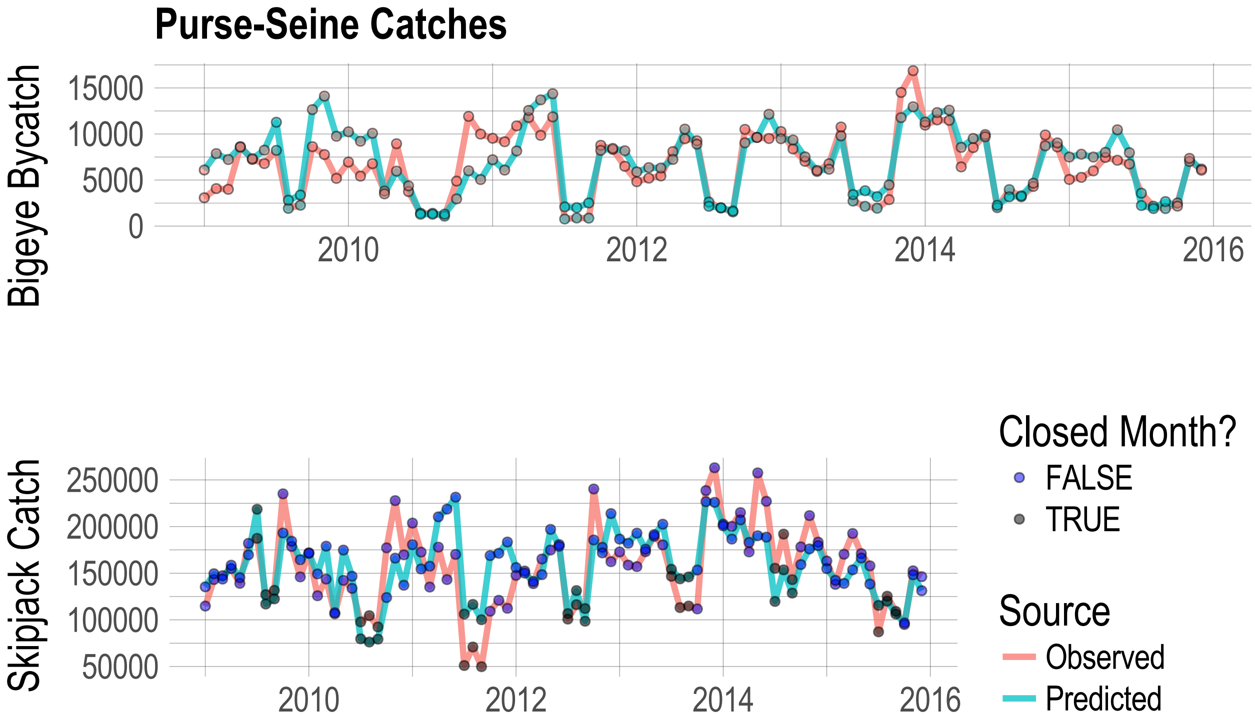

Figure 5: Observed (red) and median out of sample posterior predictive (blue) catches over time

5.2 Bargain Viability

In order to assess the viability of our proposed Coaseian bargain, we sorted our database of FAD fishing events in descending order of the ratio of bigeye bycatch saved / skipjack tuna lost, as a rough proxy for ordering our database by the marginal benefit of bigeye saved per amount of skipjack tuna lost. We then compare the surplus generated by sequentially purchasing FAD-days in order of descending benefit, starting with the days that provide the most bigeye savings at the lowest skipjack cost.

In order for a Coaseian bargain to viable, purchases of FAD days must be able to generate a positive surplus. Meaning that the willingness to accept of the skipjack fleet is less than or equal to the willingness to pay of the bigeye fleet. If the surplus is negative, then the bigeye fleet would be economically better off staying under business as usual. We find that a Coaseian bargain could result in removal of over 50% of the observed FAD days in the WCPO bigeye fishery, producing a maximum of approximately $250 million (Fig.6).

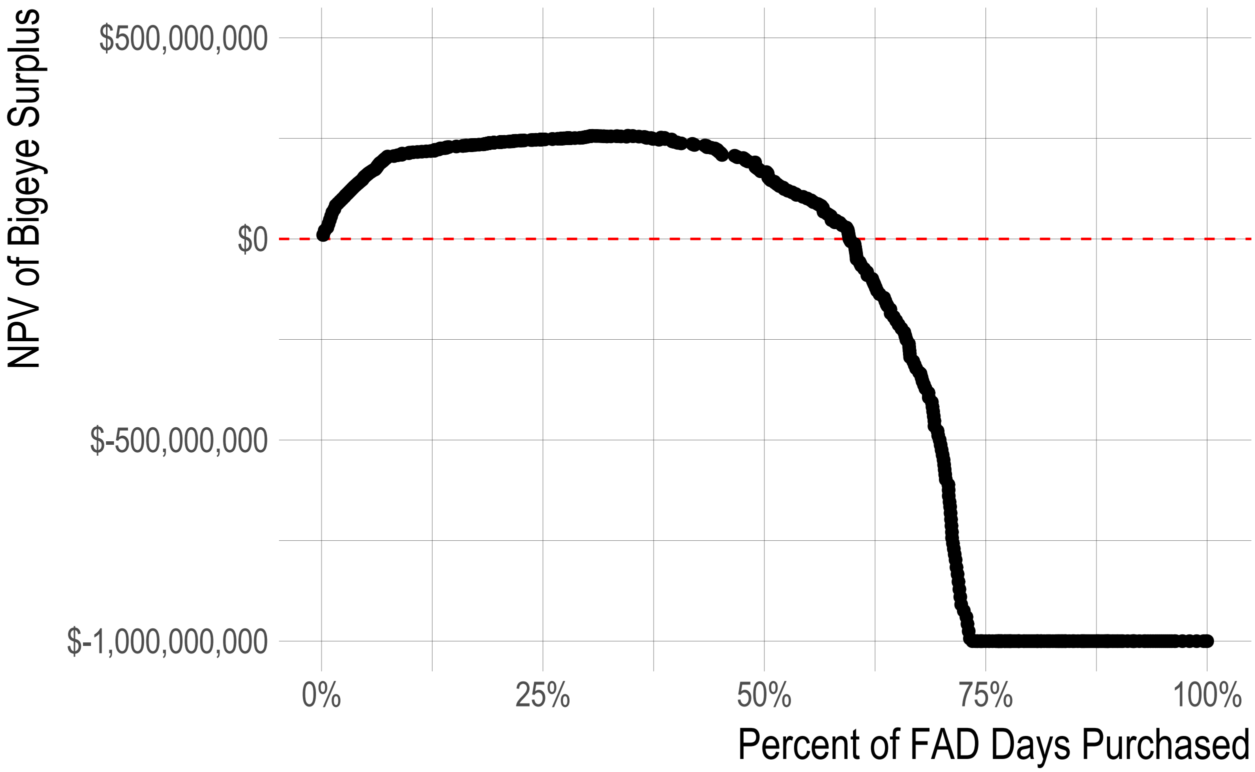

Figure 6: Bigeye surplus as a function of FAD days purchases. X-axis indicates the percentage of FAD days purchased, y-axis the resulting NPV of surplus generated for teh targeted bigeye fleet

While this indicates that a bargain is possible, it is difficult to gauge the significance of a 50% reduction in FAD days on the status of the bigeye stock itself. We can instead assess the NPV of bigeye surplus generated against the equilibrium spawning stock biomass, relative to unfished spawning stock biomass. Our results show that while a Coaseian bargain is possible, it only increases the spawning stock biomass of bigeye tuna marginally, up to approximately 7.5% of unfished SSB (up from 5% under BAU). Complete removal of all FAD days from the system would produce an SSB of approximately 15% of unfished SSB, nearing the SSB capable of producing maximum sustainable yield for this population, but the cost of achieving this increase in SSB would be far greater than the bigeye tuna interests would be willing to pay (Fig. 7).

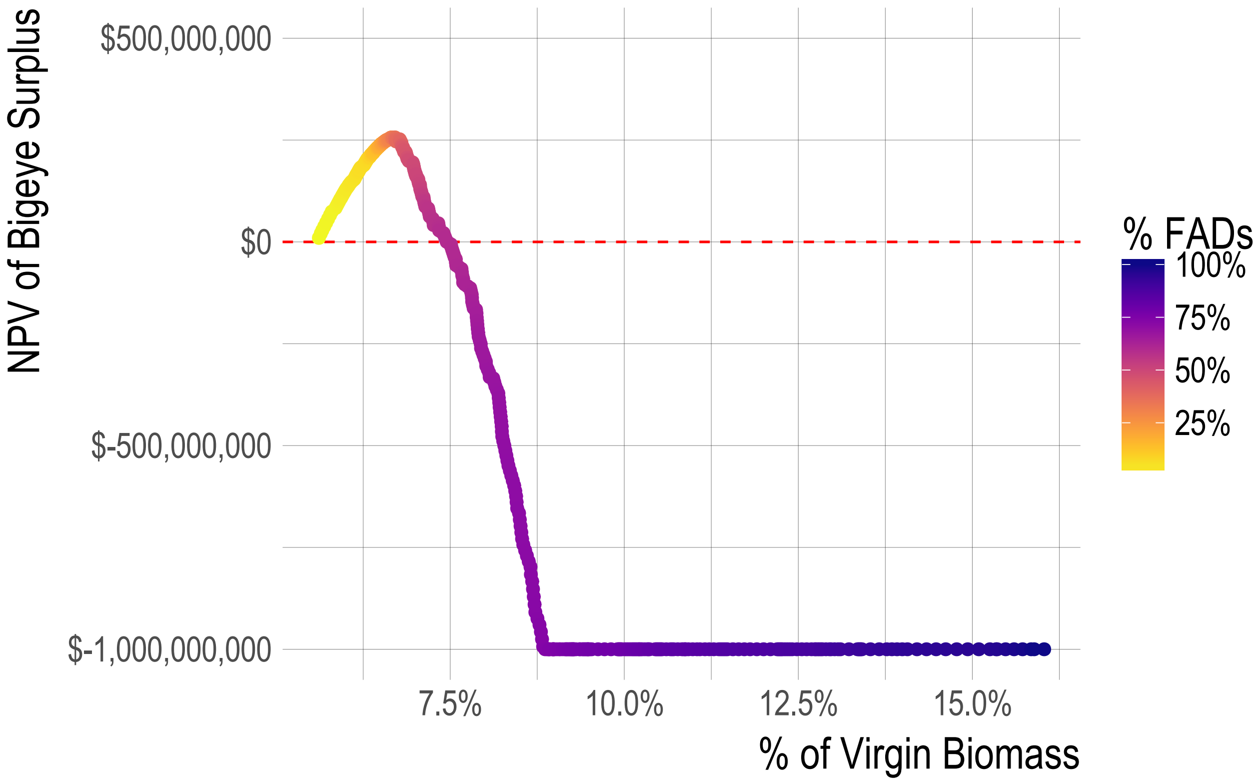

Figure 7: NPV of bigeye surplus against equilibrium spawning stock biomass relative to unfished spawning stock biomass. Color shows percent of FAD days purchased

If we are interested in conservation outcomes then, according to our additional payments would have to be made to achieve substantial increases in the amount of bigeye tuna left in the Western Central Pacific Ocean. We can calculate the % increase the ex-vessel price of long-line captured bigeye tuna that would be required to make up the deficit between the willingness to accept of the skipjack fleet and the willingness to pay of the bigeye fleet. This serves as a proxy for a "conservation tax" that could be imposed on sashimi-grade bigeye tuna. Our results suggest that this tax would have to be extremely high, up to 200%, in order to achieve levels of SSB above 15% of unfished SSB (Fig. 8).

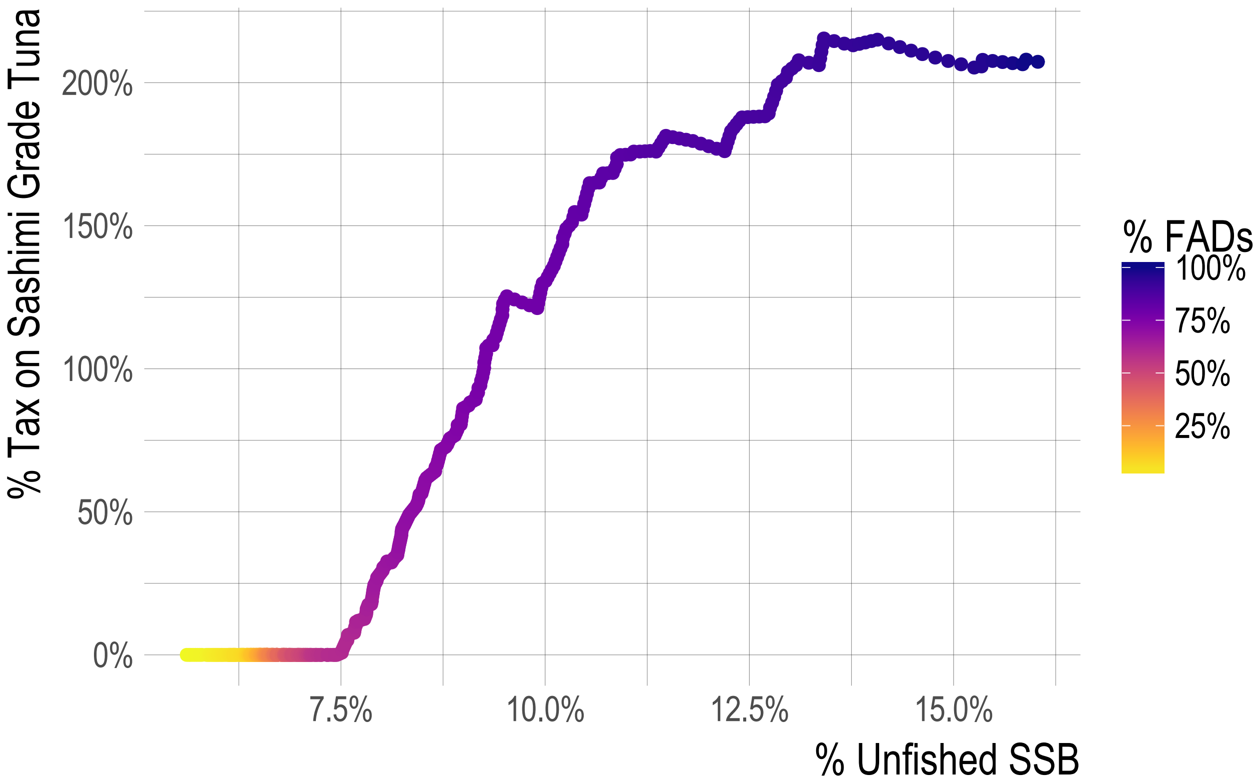

Figure 8: % Tax on long-line BET required to achieve a target spawning stock biomass relative to unfished spawning stock biomass

6 Discussion

Overfishing of bigeye tuna in the WCPO has been well established for nearly a decade. The lack of an effective regulatory solution is unsurprising though when one considers the institutional nature of the fishery. While tuna species targeted by a group of fleets with a common interest have been successfully managed, bigeye tuna are fished by fleets with competing economic interests. The result then has been inaction, with targeted bigeye fishermen unwilling to reduce catch due to the effects of bigeye bycatch, and skipjack fishermen unwilling to sacrifice skipjack catches in order to provide economic benefits that they do not capture. Under a situation with stronger property rights, a central government could simply mandate the conservation of bigeye tuna, as would be done were this a fishery managed under the Magnusun-Stevens act of the United States (though the enforcement costs of this actions bear consideration). However, given the relatively weak property rights in the WCPO, regulatory actions require collective action among the different fishing fleets targeting the shared bigeye and skipjack tuna stocks. The right economic incentives are required to generate this collective action.

A Coaseian bargain may be able to realign the incentives in the WCPO tuna fisheries. Since targeted bigeye tuna fishing interests stand to benefit from reduced bycatch of juvenile bigeye tuna, and skipjack tuna fishing interests stand to lose money through this reduction, we propose a market mechanism to allow the bigeye tuna interests to compensate the skipjack fleet, through the subsidizing of FAD-free fishing fays in the WCPO. Our results demonstrate that given a reasonably high resolution model of the system this proposed Coaseian bargain may be capable of reducing overfishing of bigeye tuna. However, the potential for the bargain as it stands is relatively small, producing at most a 2% increase in the spawning stock biomass of the population. Further reductions in bigeye bycatch could be achieved through additional FAD day purchases, though current results suggest that a nearly 200% tax would be required to achieve a spawning stock biomass near 20% of unfished levels.

How then might this bargain be implemented? At its face, it seems that a bargain would struggle at the scale discussed in this paper (the entire WCPO); wouldn't the transaction costs of organizing all the payers and payees absorb any surplus generated? There are a number of features to the WCPO that can act to substantially reduce the transaction costs of this bargain. First, the skipjack tuna purse-seine fleet. Skipjack fleets already must purchase fishing days from countries in whose EEZs they wish to fish. These fishing days are already enforced through 100% on-board observer coverage. Therefore, there would actually be relatively low additional costs of enacting a program that 1) allowed for purchase of FAD free fishing days and 2) enforcing the absence of FADs on those purchased days. The more complicated question then lies on the payee end: who would pay the subsidy on the FAD free fishing days, and how would those funds for those payments be captured?

Ideally (from the perspective of the bargain), we would like to think of the targeted bigeye fleet as a unified entity, say a cooperative, that could tax its revenues in order to fund this project. However, the WCPO long-line fleet is far less concentrated than the WCPO skipjack fleet, and as it fishes in the high seas primarily, is not subject to the purchase of fishing vessel days. Therefore, the bigeye fleet is comprised of a large number of disparate interest. Substantial transaction costs would have to be incurred to organize these interests to levy the payments required to achieve this bargain. At its face then, the disorganized nature of the targeted bigeye fleet seems to preclude this proposed bargain. The highly concentrated nature of the final market for long-line captured bigeye provides a potential avenue here.

Nearly all of the long-line captured bigeye tuna is consumer in the Japanese sashimi market. This market is supplied by an increasingly concentrated set of distributors. This means that the funds for this bargain could be obtained more efficiently by a "sustainability tax" on consumers or distributors or bigeye tuna in Japan. Surveys in the area suggest that a willingness to pay for FAD-free tuna may already exist in Japan (citations to come), and that there is precedent for this kind of action in the Japanese market (This section is hot off the press, and will get expanded on substantially).

Taken together then, our results provide a clear economic rationale for the continued overfishing of bigeye tuna: economic incentives are such that the economic costs of ending overfishing exceeds the economic benefits. It is critical to distinguish this incentive from a simpler "tragedy of the commons" problem, in which the main impediment to conservation is a lack of property rights. The WCPO tuna fleets have actually already undertaken a variety of collective actions to overcome this challenge, resulting in positive outcomes for many of the other tuna species in the region (Pons *et al.* 2016). Improving bigeye tuna then does not involve simply addressing the commons, but rather the alignment of costs and benefits among collective action members. Our results show that the economic and ecological health of the WCPO bigeye fishery could indeed be improved through a Coaseian bargain that allows for distribution of costs and benefits. However, we also show that this bargain is only capable of a relatively small improvement, and that achieving greater conservation outcomes is likely to come at an economic costs. Our results show then that fully ending overfishing of bigeye is likely to require economic trade-offs between the health of the bigeye fishery and the economic well-being of the skipjack fishery. Addressing this problem head-on in this manner allows us now to consider regulatory solutions that are best able to navigate this trade off. While a Coaseian bargain does not appear capable of solving bigeye overfishing on its own at this point, this analysis demonstrates the strength of a Coaseian perspective in assessing persistent environmental problems. Failure to consider institutional structure and the distribution of costs and benefits can lead to a misdiagnosis of the root cause of an environmental problem, limiting the ability of effective solutions to be developed. Analyses such as ours can help identity the structure of costs and benefits, allowing us to identify solutions that are best able to navigate this landscape.

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