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Tuna trade#offs: Balancing profit and social benefits in one of the world's largest fisheries

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Tuna trade-offs: Balancing profit and social benefits in one of the world's largest fisheries

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Abstract

The western and central Pacific Ocean (WCPO) tuna fishery is one of the world's largest in terms of both catch volume and value, providing over half of global tuna catch with a landed value of US \$5.84 billion in 2017. Fishing is conducted by both large- and small-scale fleets, with fisheries subsidies disproportionately benefiting the former. The primary objective of this study was to determine the optimal distribution of effort between two large-scale fisheries (LSF) and two small-scale fisheries (SSF) in the WCPO under three scenarios: to maximize industry benefits, minimize subsidization, or maximize food supply. The objective was approached using a bioeconomic game theoretic model. Results indicate opposite distributions of effort to maximize industry benefits (all fishing conducted by LSF) or to minimize subsidization (all fishing by SSF), with more balanced effort distributions to maximize food supply. Total value of capacity-enhancing subsidies in optimal scenarios ranged from \$1.4 billion when industry benefits were maximized to \$0.2 billion when subsidization was minimized. Investigation of suboptimal scenarios reveals the flexibility of these results, with wide ranges in outputted state variables for a given goal. Difficulty was encountered in modelling the SSF sector due to data deficiencies, a well recognized issue in managing SSF. Investments towards 'data equity' to help ensure that management decision-making can properly account for the SSF sector would be useful. This study has implications for the objectives we set in fisheries management, and the potential trade-offs, often value-driven in nature, that we must make explicit in that management.

Keywords

Data equity; Game theory; Shared fish stocks; Small scale fisheries; Suboptimal results; Subsidies

Table of Contents

- 1) Introduction
- 2) Background
 - a) Fishery Overview
 - b) Socio-Political Aspects of Fishery
 - c) Fisheries Subsidies
 - d) Game Theory

3) Methods

- a) Bioeconomic Model
- b) Optimization
- c) Input Data & Parameters
- d) Sensitivity Analyses

4) Results & Discussion

- a) Optimal Model Results
- b) Suboptimal Model Results
- c) Sensitivity Analyses
- d) Socio-Political Implications

5) Conclusion

Introduction

The western and central Pacific Ocean (WCPO) tuna fishery is one of the world's largest fisheries in terms of both catch volume and value, providing nearly 80% of the total Pacific Ocean tuna catch and over half of global tuna catch with a landed value of US \$5.84 billion in 2017 (Williams & Reid, 2018). The major species fished are skipjack (*Katsuwonus pelamis*, Scombridae), yellowfin (*Thunnus albacares*, Scombridae), and bigeye (*T. obesus*, Scombridae), with small amounts of albacore (*T. alalunga*, Scombridae) and Pacific Bluefin (*T. orientalis*, Scombridae) also caught. The three main species' stocks overlap geographically and are caught by both large- and small-scale fisheries (LSF and SSF, respectively) at different life stages. LSF are typically from Pacific-based domestic fleets or from foreign fleets of developed countries, with their catch and effort being well documented. In the WCPO, they fish both in exclusive economic zones (EEZs) of coastal states (for example, waters of Pacific nations) and international waters (high seas). SSF are typically from poorly-documented domestic coastal fleets, often from developing countries, and are fisheries that support local food security as well as play social and cultural roles (Bell et al., 2009; Cohen et al., 2019; Gillett & Lightfoot, 2002; Zeller, Harper, Zylich, & Pauly, 2015). This includes WCPO SSF for tuna, which in the Pacific islands and for countries such as Indonesia appear to be the most important fish by catch volume and provide important high-quality protein to food-deficit countries (Bell, Allain, et al., 2015; Charlton et al., 2016; Duggan & Kochen, 2016; Gillett, McCoy, Rodwell, & Tamate, 2001).

Effective management plans for WCPO tuna must consider both sectors due to the overlap in target stocks and the socio-economic importance that both sectors demonstrate. Despite this, several

barriers exist to ensure consideration of the SSF sector in decision-making, and we highlight here two main ones. Firstly, the highly dispersed and often poorly regulated nature of SSF in many countries leads to difficulties in generating good data that allows for models and decision-making to understand and prioritize the sector (see Bailey, Flores, Pokajam, & Sumaila, 2012 for a discussion about this in Indonesia; Bush et al., 2017). We come back to this issue later in the paper. Secondly, the widespread subsidization of fisheries disproportionately benefits LSF, which may result in LSF and SSF not being represented or prioritized evenly in fisheries management. Worldwide, marine fisheries subsidies were estimated at \$35 billion in 2009, which represents 30-40% of those fisheries' total gross revenue (Kelleher, Willmann, & Arnason, 2009; Sumaila, Lam, Le Manach, Swartz, & Pauly, 2016). Of these, SSF received only about 16% overall and approx. 10% of capacity-enhancing subsidies, known to promote overcapacity and overfishing (Schuhbauer, Chuenpagdee, Cheung, Greer, & Sumaila, 2017). The remainder went to LSF. By contrast, SSF land approximately half of global catches and employ over 90% of the world's 51 million fishers with little to no discards, i.e. less waste and more food (Chuenpagdee, Liguori, Palomares, & Pauly, 2006; FAO, 2012; Gillett, 2011; Jacquet & Pauly, 2008). Furthermore, capacity-enhancing subsidies reduce the net economic value of fisheries as society ends up bearing the cost of subsidization (Sumaila et al., 2010). But not only are there economic costs of subsidization, so too may there be ecological costs, as capacity-enhancing subsidies promote overfishing.

The primary objective of this study is to determine the optimal distribution of effort between two LSF (longline and purse seine) and two SSF (handline and small scale surface) catching tuna in the WCPO under three scenarios: to maximize industry benefits, minimize subsidization, or to maximize food supply. Industry benefits were considered to be the fishery profit (more specifically the resource rent, but we use industry profit here for a general audience) by gear, not considering subsidies. Fixed rate subsidies by gear and species were then considered to optimize effort by gear such that the profit minus subsidies was maximized. The final optimization scenario simply maximized catch across all species and gears within model constraints without considering profit or subsidies. Secondary objectives were to investigate the impact of these three optimizations on tuna populations and direct fisheries sector employment. The WCPO was selected for consideration as it has the world's largest tuna fishery, providing both subsistence and luxury food products, and has relatively comprehensive data available. Furthermore, the Regional Fisheries Management Organization responsible for the WCPO, the Western and Central Pacific Fishery Commission (WCPFC), seeks to ensure the long-term conservation and sustainable use of these tunas. This study explored the implications of pursuing differing socially- or economically-motivated fisheries objectives to investigate the trade-offs between objectives. A

bioeconomic game-theoretic equilibrium model was developed, which allows for simultaneous consideration of gears and species to determine what ecological, economic, and social impacts are likely to result from fishing efforts. This study expanded on such a model developed by Bailey et al. (2013) to investigate the WCPO tuna fishery, including LSF and SSF and is, to the authors' knowledge, the first bioeconomic game theoretic model to include subsidies as a parameter. We start by providing a further background on the fisheries of interest, before describing the model and presenting the predicted effort distributions and economic, ecological, and social outcomes for each of the management scenarios.

Background

Fishery Overview

The equatorial waters of the WCPO (c. 10°S to 10°N) are home to three major tuna fisheries: skipjack, yellowfin, and bigeye. Total reported catches over the past decade have been fairly stable around 2.5 MT (million metric tonnes) (Brouwer et al., 2018; Williams & Reid, 2018). Of this, the 2017 catch was 64% skipjack, 27% yellowfin, and 5% bigeye. All three species of interest are caught by purse seine and small scale fisheries, with yellowfin and bigeye additionally caught by longline. The purse seine fleet dominates total catch (1.81 MT, 71% of total 2017 catch) due to large catches of skipjack. It operates almost exclusively in equatorial waters, while the longline fleet (0.24 MT, 9%) covers a wider latitudinal range. Within its equatorial range the longline catch is similarly distributed between yellowfin and bigeye. Other LSF in the region are pole-and-line and troll fisheries, which were excluded from this study due to low overall catches (6% and <1%, respectively). Specifically, the pole and line fishery had relatively low proportions of the catch by species compared to longline (<8% for each of the three tunas compared to longline's 46% of bigeye and 14% of yellowfin catch). Data on small scale tuna fisheries are lacking but indicate that over the entire WCPO the catch is c. 514,000 t, dominated overall by Indonesia and the Philippines (c. 470,000 t/year), and in the central Pacific region by Kiribati (c. 12,000 t/year) (Gillett, 2011). The proportion of tuna and tuna-like fish in Pacific Island SSF catch ranges from 30% (Fiji) to 100% (Tokelau). These small scale fisheries are considered to be "those fisheries that use vessels that are open or partially undecked, or vessels that use outboard engines or sails, or vessels that fish with handlines, rod-and-reel gear, harpoons or similar non-industrial gear" (Gillett, 2011) and are primarily multi-species fisheries where all catch has economic or food value. This results in few to no discards (literally catch thrown overboard), though catch should still be monitored for bycatch of ecologically sensitive species to preclude population reduction. This is especially pertinent for SSF gillnets, which have been identified as generating high levels of bycatch (Shester & Micheli, 2011). This study

considered handline and small scale surface fisheries as two prominent SSFs for which data on catch composition is available or has been estimated. Small scale surface fisheries were considered to include gears such as ring nets and gillnets.

Skipjack are the dominant WCPO fished species by weight. In contrast to other tuna in the region, stock assessments have consistently predicted they exceed reference points for management, both in terms of stock status and exploitation rate (McKechnie, Hampton, Pilling, & Davies, 2016). They are the smallest and earliest maturing of the three tunas of interest, grow fast, and spawn in tropical waters throughout most of the year (Fromentin & Fonteneau, 2001; Hunter, Macewicz, & Sibert, 1986; K. M. Schaefer, 2001; M. Schaefer & Orange, 1956). These life history characteristics have ensured stocks remain at sustainable levels despite heavy fishing pressure, resulting in a least concern conservation status by the IUCN, and an assessment in the WCPO as neither overfished nor experiencing overfishing (Collette, Acero, Amorim, Boustany, Canales Ramirez, Cardenas, Carpenter, de Oliveira Leite Jr., et al., 2011; McKechnie et al., 2016). Yearly catch over the past decade has ranged from 1.6 to 2.0 MT (Williams & Reid, 2018). Catch by weight is dominated by purse seiners (c. 80% of total catch), whose catch size mode is 40-60 cm. A similar number of individuals are caught by the domestic fisheries of Indonesia and the Philippines. However, these are younger fish of approx. 20-30 cm and thus yield a lower total weight (c. 10% of total catch). The remainder of the catch is pole-and-line (8% of total catch) with less than 1% of total catch by longline. The estimated value of the fishery across gears was US \$2.98 billion in 2017. About 80% of skipjack go to canneries (Guillotreau, Squires, Sun, & Compeán, 2017).

Yellowfin are the second largest WCPO tuna fishery by weight, with recent catches c. 600,000 t/year (Williams & Reid, 2018). They school by size, with smaller individuals commonly schooling with skipjack and juvenile bigeye, especially around floating objects. This has led to purse seiners targeting skipjack or yellowfin catching c. 70% of yellowfin by weight (Williams & Reid, 2018). Floating object or fish aggregating device associated purse seiners catch individuals around c. 40-90 cm, while non-associated sets catch larger individuals >90 cm (Williams & Reid, 2018). Juvenile yellowfin catch by purse seiners has been a topic of conservation concern (Bailey et al., 2012, 2013) but the stock is not currently considered to be overfished or experiencing overfishing (Tremblay-Boyer, McKechnie, Pilling, & Hampton, 2017), and is considered to be well managed (Collette, Acero, Amorim, Boustany, Canales Ramirez, Cardenas, Carpenter, Chang, de Oliveira Leite Jr., et al., 2011). The implications of fish aggregating devices for management of skipjack, yellowfin, and bigeye has already been investigated in a game-theoretic model by Bailey et al. (2013) and therefore was not considered in this study. The

remainder of the catch is split approximately evenly between longline and “other” gears including handline, troll, ring nets, and gillnets (Williams & Reid, 2018). These “other” gears dominate the catch in domestic waters of Indonesia and the Philippines. Here, the surface fisheries take large numbers of small individuals c. 20-50 cm, while handline fisheries take smaller quantities of adults >110 cm. The size distribution of longline catch is similar to handline but starts smaller at c. 90 cm. Yellowfin’s value per tonne is about twice that of skipjack, resulting in an estimated value of the fishery across gears in 2017 of US \$1.9 billion (Williams & Reid, 2018). Large yellowfin command a price premium, resulting in longline and handline catch value per tonne greatly exceeding that of the small individuals caught by purse seine or surface fisheries, which are close to the per tonne value of skipjack. These smaller individuals are more likely to go to canneries, which take about 50% of the yellowfin catch (Guillotreau et al., 2017), while larger individuals are sold for higher-price sashimi.

Bigeye are the largest of the three tunas considered and command the highest market value per tonne. Their yearly catch has been fairly stable since the late 1990s, ranging from c. 130,000 t to 190,000 t (Williams & Reid, 2018). As with yellowfin, there are conservation concerns relating to the catch of juvenile bigeye by purse seiners employing fish aggregating devices (Bailey et al., 2012, 2013), which have contributed to its global listing as vulnerable by the IUCN under criterion A for a declining population trend (Collette, Acero, Amorim, Boustany, Canales Ramirez, Cardenas, Carpenter, Chang, Chiang, et al., 2011, although note that recent assessments rely on an updated growth model and have different conclusions). Despite these concerns, WCPO bigeye are considered not overfished or experiencing overfishing under current growth models (Vincent, Pilling, & Hampton, 2018). Longline and purse seine fisheries each catch c. 45% of total catch with the remainder spread across pole-and-line and various gears in the Philippine, Indonesian, Vietnamese, and Japanese domestic fisheries (Brouwer et al., 2018; Williams & Reid, 2018). Similar to the other two tunas, Philippine and Indonesian domestic fisheries take large numbers of small individuals c. 20-60 cm, while purse seiners catch individuals of c. 40-110 cm and longliners catch large adults >90 cm (Williams & Reid, 2018). Unlike yellowfin, however, catch of large individuals by handline in the Philippines is relatively small. The total value of bigeye fisheries across gears in 2017 was estimated to be US \$0.65 billion. As with yellowfin, larger bigeye have a greater value per tonne than smaller individuals and are likely to go to luxury markets such as those for sashimi (Guillotreau et al., 2017; Schiller, Bailey, Jacquet, & Sala, 2018).

201 Socio-political Aspects of Fishery

202 The WCPO fisheries are managed by the Regional Fisheries Management Organization the
 203 Western and Central Pacific Fisheries Commission (WCPFC), established in 2004 under the Convention
 204 for the Conservation and Management of Highly Migratory Fish Stocks. Consisting of 26 member
 205 nations, 7 participating territories, and 6 cooperating non-members, it seeks to address management
 206 problems resulting from e.g. unregulated fishing, insufficiently selective gear, and excessive fleet
 207 capacity. The objective is long-term conservation and sustainable use of highly migratory fish stocks (e.g.
 208 tunas), with secondary socially- or economically- motivated objectives stated in the Convention text.
 209 While states are mandated to try to cooperate in tuna management through the WCPFC, tuna
 210 management is also a sub-regional and domestic issue. Individual states must enact regulations and
 211 manage fisheries and data programs in compliance with WCPFC but also in pursuit of their own
 212 domestic objectives. Additionally, many Pacific states are also part of sub-regional groups like the
 213 Parties to the Nauru Agreement (PNA) and Forum Fisheries Agency (FFA), which use their collective
 214 bargaining power at the WCPFC to push for conservation and management measures that support their
 215 interests vs. that of distant-water fishing nations (Miller, Bush, & van Zwieten, 2014; Yeeting, Weikard,
 216 Bailey, Ram-Bidesi, & Bush, 2018). This leads to system of multi-level governance in the area that
 217 complicates full cooperation (Bailey, Miller, Bush, van Zwieten, & Wiryawan, 2016), but is necessary to
 218 maintain sovereignty and collective action.

219 The western part of the WCPFC Convention Area overlaps with the Coral Triangle region, an area
 220 of high biodiversity and productive tuna populations in archipelagic areas (Bailey et al., 2012). In 2004,
 221 estimates suggested that over 150 million people lived in the Coral Triangle region, and that about 2.25
 222 million fishers depended on marine resources for their livelihood (The Nature Conservancy, 2004).
 223 Sustainable fisheries management regimes are therefore important in an effort to provide the
 224 population with continued benefits from regional fisheries, which include valuable tuna fisheries. In the
 225 Pacific, tuna may be considered “not only *a* key resource but often *the* key resource”, providing essential
 226 employment, subsistence, and income (Gillett et al., 2001, p. vi). These tuna fisheries produce about ten
 227 times the amount of fish and have over seven times the value as all other fisheries of the region
 228 combined. This value is from both local fisheries (LSF and SSF) and access fees paid by foreign fleets.
 229 Multiple studies have highlighted the importance of tuna to food security and public health, with calls to
 230 increase per capita consumption (Bell, Allain, et al., 2015; Bell et al., 2009; Pilling, Harley, Nicol, Williams,
 231 & Hampton, 2014). Skipjack is the primary tuna caught and eaten (Gillett et al., 2001). Quantitative

reports of catch from coastal and small scale fisheries in Pacific Islands used to be largely guesswork, especially for subsistence fisheries, but monitoring programs have started to emerge in recent years (Gillett & Tauati, 2018). Over all species of fish caught, 12 out of 14 Pacific Island countries and territories have estimated coastal subsistence catches greater than coastal commercial catches. Yet while these fisheries are thus anecdotally important, the lack of data on subsistence catches underlines the importance of bioeconomic modelling to fill gaps in existing datasets and quantify the importance of this type of fishing. Tuna, being pelagic, do not necessarily form the main catch for these coastal fisheries, but authors argue that the declining catches of overfished stocks of coastal species could be supplemented by nearshore FADs concentrating tuna in locations accessible to SSFs (Bell, Albert, et al., 2015).

Southeast Asia also relies heavily on fish as a primary source of protein. However, most nearshore fisheries in this area are overfished. Overcapacity in SSF is a leading cause, driven by factors including poverty, dependence on the fishery for food and livelihood, and lack of alternative employment (Pomeroy, 2012). Competition with highly efficient and subsidized LSF can reduce the proportion of fish stocks available to SSF. When considering tuna, this competition can occur even when LSF are based up to thousands of km away, as shown by tagging studies (Leroy et al., 2016; McKechnie et al., 2016; McKechnie, Pilling, & Hampton, 2017; Tremblay-Boyer et al., 2017). Globally, overfishing by LSF has harmed food security, especially in low-income and small island nations which are heavily dependent on fish protein (Srinivasan, Cheung, Watson, & Sumaila, 2010). Asia was one of the regions to incur greatest losses over 1950-2004. Without large-scale overfishing, the 2000 catch of low-income, food-deficit nations may have been up to 17% greater (Srinivasan et al., 2010). In the case of tuna, which are harvested by foreign LSF in both EEZs and the high seas of the WCPO, the high seas catch likely plays a negligible role in addressing food security (Schiller et al., 2018). Within Asian countries including the Philippines and Vietnam, the higher value of LSF catch may contribute to less affordable fish for low-income consumers (Dey et al., 2008). Therefore, in order to meet food security and other social needs in WCPO countries, adequate fishable biomass must be available to SSF (others have suggested that trade of fish may contribute to food security indirectly (Asche, Bellemare, Roheim, Smith, & Tveteras, 2015), an option not explored in this paper).

Fisheries Subsidies

Fisheries subsidies are defined as financial contributions by the public sector that provide private benefits to the fisheries sector (Kelleher et al., 2009; WTO, 1994). These can be considered as

beneficial, capacity-enhancing, or ambiguous in nature (Sumaila et al., 2010). Beneficial subsidies lead to investment in the natural capital of fisheries, including management programs, research, and the development and maintenance of marine protected areas. Capacity-enhancing subsidies lead to 'disinvestment' in the fishery resource by artificially increasing the profitability of fishing through e.g. fuel subsidies, boat or port construction, or price and marketing support. Ambiguous subsidies may lead to investment or disinvestment and include fisher assistance or vessel buyback programs.

Capacity-enhancing subsidies, including fuel subsidies, generally lead to increased efforts and greater stock depletion, resulting in overcapacity and overfishing (Clark, 2006; Davis, 2014). These effectively counter the economic incentive to cease fishing when it becomes unprofitable to the industry (Kelleher et al., 2009), meaning that subsidized fleets fish longer or harder than would otherwise be worthwhile from a financial standpoint. The value of these subsidies exceeds those of beneficial and ambiguous subsidies, largely due to the prevalence of fuel subsidies (Sumaila et al., 2016). Developed countries account for 65% of the total global subsidy with the major subsidizing countries/entities being the European Union, Japan, and China. SSF, many of which are in developing countries, are estimated to receive only 16% of all subsidies and 10% of capacity-enhancing subsidies, despite employing over 90% of the world's fishers (FAO, 2012; Schuhbauer et al., 2017). A reduction or elimination of capacity enhancing subsidies could thus improve biological and economic sustainability of global fisheries with little negative impact on SSF.

Subsidies to tuna fisheries in the WCPO have been estimated as US \$1.5 billion in 2009, over one-third of the estimated yearly fishery landed value (\$4.1 billion) (Sumaila, Dyck, & Baske, 2014). Landed value is often the measure reported and considered when evaluating the profitability of a fishery. However, this gives a false perception of the value of the fishery to society. Economic rent is the more representative measure, i.e. revenue minus the cost of fishing, including the opportunity cost of inputs like labour. This can be calculated from the perspective of the fishing industry (private rent) or society (social rent), since while the former receives the benefits of subsidization, the latter funds it. Returning to the WCPO tuna in 2009, total costs were estimated at \$3.3 billion (Sumaila et al., 2014), and private rent was therefore \$0.8 billion (landed value minus costs). Social rent, by subtracting the subsidized amount, further reduces the net benefit of the fishery, resulting in a \$750 million loss to society.

The extent to which society as a whole benefits from a commercial fishery is not well understood. While some researchers have examined the 'multiplier effect' to analyse how a dollar

generated in the fisheries sector is amplified throughout the economy (e.g. Dyck & Sumaila, 2010), this does not shed light on social benefits because it does nothing to analyse the trade-off in obtaining that dollar of output: what government expenditures supported that level of production and what is the opportunity cost of such expenditure? If we thought about transferring capacity enhancing subsidy payments to beneficial subsidies, such as data collection and data management, monitoring and enforcement, etc., we would still use public funds to support the fishery, but do so in a way that promotes sustainability. Alternatively, money from capacity-enhancing subsidies could be divested from fisheries altogether and used instead for other projects of social importance, such as health care or education.

Game Theory

Game theory is a tool for analyzing problems of strategic interaction between players. It is relevant to fisheries management, as fisheries represent a common pool resource which may be managed between players such as fishers, fishing industries, or nations. A fish stock is affected by the decisions of each of these players in terms of when, how and what quantity of fish they catch. Each player must then take into account not only their actions but also those of the other players, a situation referred to as dynamic externality (Levhari & Mirman, 1980). A game is considered cooperative if the players discuss and agree upon a joint plan which is binding and enforceable (Nash, 1953) and non-cooperative when these conditions are not met (Nash, 1951).

Game theory has been applied to the field of fisheries management for 40 years (Bailey, Sumaila, & Lindroos, 2010; Hannesson, 2011), including tuna fisheries (Bailey et al., 2013; Duarte, Brasão, & Pintassilgo, 2000; Klieve & MacAulay, 1993). Tuna are well suited to analysis through the lens of game theory since many interested parties harvest this transboundary, highly migratory species (Munro, 1990). Past studies have focused on the private rent obtained by optimizing fishing effort and sustainable exploitation levels. Here, we build on previous applications but instead optimize effort for both the private and social rents of tuna fisheries in the WCPO by also considering fisheries subsidies. Furthermore, a third optimization to maximize total yield was explored in light of increasing issues of food security across WCPO nations (Bell et al., 2009). Recent years have seen many calls to reduce capacity-enhancing subsidies worldwide (cf. UN Sustainable Development Goals, Goal 14, Target 14.6 (UN, n.d.)) and to support SSF, which are critical for subsistence, employment, and culture in many low-income regions (Chuenpagdee, 2011). This study optimized fishing effort over four players, that is, two LSF (longline and purse seine) and two SSF (handline and small scale surface) in the WCPO. These gears

were chosen to define players because dynamic externality exists between them as they all target or catch yellowfin, bigeye and skipjack tuna (except for longline which has minimal skipjack catch). All scenarios investigated in this study were modelled as cooperative games. This was to effectively investigate the impact and trade-offs of various objectives for the fishery, assuming that all players agreed to the objectives. No other fishing activity, including illegal or unreported fishing, was assumed to occur.

Methods

Bioeconomic Model

A bioeconomic game theoretic model was developed to address the main objectives of the paper, based on Bailey et al., 2013. The Bailey et al. model had three players (i.e., gears: longline, purse seine, and handline) fishing across three species (skipjack, yellowfin, bigeye), with age-structured growth, recruitment, and mortality. Growth was assumed to follow the von Bertalanffy model and recruitment the Beverton-Holt model (1957). See Bailey et al., 2013 or supplemental text for population dynamics model, parameters, and associated assumptions. Fishery selectivity at age by gear and species in this analysis was modified from Bailey et al. to reflect recent reports of size-specific vulnerability, and to include the new gear small-scale surface fisheries. Selectivity was modelled as either an asymptotic logistic or dome-shaped three parameter logistic function (Figure 1; see Bailey et al. (2013) or supplemental for more details). The model did not consider spatial variation in stocks or fishing over the equatorial WCPO as individual tuna can move thousands of kilometers as shown by tagging studies (K. Schaefer et al., 2015) and are modelled as single stocks in WCPFC recent stock assessments (McKechnie et al., 2016; Tremblay-Boyer et al., 2017; Vincent et al., 2018). Model parameters can be found in Tables 1-3, along with the values used in the model as sourced from academic literature, stock assessments, and reports. The state variables of interest in the simulations include private and social resource rent (with and without considering subsidies, respectively), yield, biomass, and employment.

The yield of species s for a specific gear g was calculated as:

$$Y^{s,g} = R_e^s \phi_{VB}^{s,g} F^{s,g}$$

Where R_e^s is the number of recruits, $\phi_{VB}^{s,g}$ is the per-recruit gear-specific yield for one unit of fishing effort, and $F^{s,g}$ is the fishing mortality. See Bailey et al., 2013 or supplemental text for the calculations of these parameters.

Total revenues TR^g and costs TC^g per gear were calculated as: $TR^g = \sum_s Y^{s,g} p^{s,g}$

$$TC^g = c^g f^g$$

Where $Y^{s,g}$ is the yield by species and gear, $p^{s,g}$ is the ex-vessel price by species and gear, c^g is the unit cost of fishing by gear, and f^g is the fishing effort by gear.

Private rent PR^g per gear was the difference between total revenues TR^g and costs TC^g summed over the three species:

$$PR^g = \sum_s TR^g - TC^g$$

Social rent SR^g per gear was calculated as

$$SR^g = \sum_s TR^g (1 - \lambda^{s,g}) - TC^g$$

where $\lambda^{s,g}$ is the subsidy intensity. This is calculated as the sum of capacity enhancing and ambiguous subsidies as a proportion of revenue per species and gear. Details of its calculation are provided in the input data & parameters section. Subsidy intensities were considered to be fixed values. All monetary values are USD. Note that prices were assumed to be independent of catch volume, and remained constant throughout the model, though inverse relations have been identified between amounts and values of WCPO tuna catch (Sun et al., 2017).

To evaluate the model's performance, it was first simplified to a two gear model including longline and purse seine, with current effort values as inputs (4×10^8 hooks/year and 5.2×10^4 days/year, respectively (SPC-OFP, 2018)). The outputted yields were then compared to reality. Resulting catches by gear and species were within 4% of actual values with the exception of longline catch of bigeye (81% of current). This is likely due to catch outside of the target equatorial range (primarily north, near Japan) (Williams & Reid, 2018). The total landed value was \$4.5 billion, of which \$1.2 billion was longline (82% of current) and \$3.3 billion purse seine (95% of current) (Table 4, Figure S1). These catch and landed value results indicate that the model can accurately reproduce key fisheries variables. Subtracting costs

gives a private rent (PR) of \$3.0 billion. Social rent (SR) was \$2.0 billion, indicating that current subsidization is resulting in about a 33% loss of profit to society.

Optimization

Fishing effort per gear was optimized cooperatively in the bioeconomic model to maximize the total PR, SR, or yield across all gears and species. For each gear, evenly-spaced, 20 level incremental efforts ranging from 1 to a maximum value were used as input. These maximum values were selected iteratively such that they were always higher than the “optimal” efforts across all scenarios. All permutations of effort per gear were entered into the model (i.e. a $1.6e5$ by 4 matrix), then the output with the greatest variable of interest (PR, SR, or yield) was identified and its input effort scenarios per gear used to determine subsequent model results. The model was limited by two constraints: (1) that PR for any gear could not be negative and (2) that the total catch of each species could not exceed 80% of their maximum sustainable yield (MSY). The 80% MSY limit was used in accordance with the precautionary principle, which is formally recognized by the WCPFC convention (2000), and in recognition that, due to lags in catch reporting, fisheries are likely to exceed catch limits. Using a limit of 80% of MSY therefore should keep total catch under MSY even with reporting lags. All modelling, analysis, and plotting were conducted with R version 3.5.1 (R Core Team, 2018) with plots using the packages *ggplot2* (Wickham & Chang, 2015), *plotly* (Sievert, 2018), *gridExtra* (Auguie, 2017), and *viridis* (Garnier, 2018). The model’s R script is available on GitHub (Willis & Bailey, 2019).

Input Data & Parameters

Biological and LSF data and parameters were primarily obtained or derived from recent stock assessments and WCPFC summary reports as cited in Tables 1-3. Mortality was calculated as 1.5 time the growth coefficient (K). This is based on the average ratio of mortality to K for tuna (Thorson, Munch, Cope, & Gao, 2017). The Sea Around Us database was used as a secondary comparison source to calculate global costs and ex-vessel prices by species and gear (Lam, Sumaila, Dyck, Pauly, & Watson, 2011; Pauly & Zeller, 2015) and as the primary source for subsidy intensities ($\lambda^{S,g}$) (Sumaila et al., 2010). Subsidy intensities represent the proportion of landed value that was subsidized. For the purposes of this study, only capacity-enhancing and ambiguous subsidies were considered to detract from social rent. Beneficial subsidies were not considered to detract from social rent as they are an investment in the long term sustainability of a common pool resource. Subsidy intensities were calculated from the Sea Around Us database by taking global catch-weighted means of intensity by gear and species. These global estimates of subsidy intensities were assumed to be representative of the WCPO as this is where

the majority of fishing activity of the gears and species of interest to this study occur. For example, the catch weighted mean of all subsidy intensities in the database for purse seine-caught skipjack would be used here for lambda. Recall that the intensity is the proportion of the catch that is subsidies. An intensity of 0.5 would mean that for every unit of landed value, for a given species and gear, half of that value was subsidized.

Catchabilities were calculated using the equation

$$q = \frac{h}{Ex}$$

where q is catchability, h is harvest, E is effort, and x is spawning stock biomass. All three values were averaged over the years since c. 2010 to reduce the impact of yearly variability. Longline effort was measured in hooks, all other gears' efforts were measured in days as these are the standard in fishery reporting. Unit cost of effort was \$1 per hook for longline and \$22,000 per day for purse seine following Bailey et al. (2013) based on Reid, Vakurepe, & Campbell (2003).

SSF data and parameters were generally not directly available in the literature or existing databases. As indicated in the introduction, some values such as targeted sizes by gear were obtained. Other values were reported as broad approximations of SSF relative to LSF. These included the subsidisation of SSF relative to LSF, which is approximately 10% of the average for capacity-enhancing subsidies (Schuhbauer et al., 2017). Subsidy estimates calculated from the Sea Around Us database (Pauly & Zeller, 2015; Sumaila et al., 2010) varied by gear, so the average subsidy intensity by species was calculated across all gears then multiplied by 0.1 to estimate SSF subsidies by species. Subsidy intensity between the two SSF was not assumed to differ as both would benefit similarly from subsidies e.g. for coastal infrastructure or fuel. SSF values which were not available at the level of detail required were (1) the total harvest and effort levels required to calculate catchabilities, (2) ex-vessel prices, and (3) unit costs of efforts. Catchability of small-scale surface fisheries was estimated as 1% of purse seine values to approx. area of tuna stock ranges accessible to small, nearshore vessels and to account for reduced technology available to locate and catch schools. A sensitivity test was used to evaluate this assumption, details below. Handline fishery catchabilities were initially entered into the model as these same values and then adjusted after viewing catch compositions with varying fishing efforts to approximate the actual relative species composition of handline catch based on Williams and Reid (2018). Catchabilities by both gears were compared to calculated estimates using coarse resolution catch and effort data across species for some SSF (SPC-OFP, 2018). Ex-vessel prices for SSF were

assumed to be the values of the most similar LSF (handline-longline, small scale surface-purse seine) minus US \$300 /t to account for reduced market access and product quality (assumed based on anecdotal information and field work experience by the second author). Unit cost of effort for SSF was the most difficult parameter to estimate. Expert opinion on costs per fishing day varied from less than \$10 to \$230 with no clear idea of a weighted mean value due to high cost variability (F. Tolentino-Zondervan, J. Ingles, pers. com.). One hundred dollars per day was used for both SSF as it was an approximate midpoint of the estimated values and in keeping with the \$100 per day handline cost estimate in Bailey et al. (2013). Cost values were further considered for sensitivity analysis, described below.

Direct employment by gear per unit effort was estimated based on longline and purse seine vessel data from the WCPFC and reported ratio of global SSF to LSF employment per similar catch of 24:1 (Chuenpagdee et al., 2006; Jacquet & Pauly, 2008). This ratio matches estimates from FAO reports of SSF employing 90-99% of the world's fishers (FAO, 2012; Gillett, 2011) and was assumed to be representative of WCPO tuna fisheries as no better estimate was available. Crew per unit effort for the two LSF was calculated using the average number of crew per vessel (available at <https://www.wcpfc.int/record-fishing-vessel-database>) multiplied by the number of licenced vessels and divided by the average annual effort (Brouwer et al., 2018; SPC-OFP, 2018). This resulted in an estimated 1.112×10^{-4} jobs per longline hook and 0.1875 jobs per purse seine fishing day. The total yearly WCPO SSF catch is c. 0.5 MT the total longline plus purse seine gears is c. 2.0 MT (Gillett, 2011; Williams & Reid, 2018). Multiplying this by the 24:1 ratio gives a relative index of 12 fishers/t for SSF and 2 fishers/t for LSF, or 6 times the number of fishers per tonne by SSF. Therefore, the employment per fishing day by SSF was assumed to be the purse seine jobs per day multiplied by 6, which is 1.125 jobs per fishing day. Longline jobs per unit effort were excluded from this calculation as effort was measured in hooks. Indirect or secondary employment (e.g. canning operations) was not considered.

Sensitivity Analyses

Sensitivity analyses were conducted on the catchability coefficients of small scale surface fleets and the costs of SSF. To evaluate the assumed relationship between the catchability coefficients for purse seiners and small scale surface fleets, the 1% relation was also modeled as a 0.5% and 2% relation (i.e. half or double the primary value). Furthermore, costs per unit effort were considered to be the input parameter of greatest uncertainty, especially for the SSF. To account for possible underestimation, one or both SSF costs were increased from \$100 per day to \$200 per day and the model rerun.

Additionally, an increase in longline costs from \$1 per hook to \$2 per hook was independently considered to account for cost variability between fishing nations (Reid et al., 2003). Note that we did not model the potential impacts of a cost overestimation, i.e., if our input costs were in fact too high.

Results & Discussion

Optimal Model Results

Optimized fishing efforts over all four gears varied greatly depending on scenario objective: PR, SR, or yield. To maximize PR, effort optimization placed all effort distributed between the two LSF (longline and purse seine), while maximizing SR resulted in all effort in the two SSF (handline and small scale surface; Table 4, Figure 2). Optimizing effort to maximize yield resulted in the most even distribution of effort across gears. The least PR and yield were obtained when optimizing effort to maximize SR, the latter of which can be attributed to its low skipjack catch. Otherwise the distribution of catch by species was similar across scenarios, with only a 0.06 MT difference in total catch between the PR and yield scenarios. The state variable with the greatest variability was the estimated number of jobs generated by each scenario, which was almost three orders of magnitude higher in the maximum SR scenario than in the maximum PR due to the increased number of fishing days and workers per unit effort by SSF compared to LSF.

Varying vulnerability (Figure 1) to each of the four gears resulted in differing age distributions of fished tuna between scenarios (Figure 3). The distribution of skipjack catch is shifted towards older individuals in the maximum PR scenario, while the other two scenarios catch younger individuals with the greatest yield by age at one year old. For yellowfin and bigeye, the catch is more even by age in the maximum PR scenario but becomes more bimodal in the maximum SR and yield scenarios as small scale surface fisheries catch 0-1 year-olds and handliners catch 4+ year-olds. This reinforces the two dichotomies between gears: (1) LSF vs SSF and (2) gears which catch skipjack and associated juvenile yellowfin and bigeye (purse seine and small scale surface) vs gears which catch adult yellowfin and bigeye (longline and handline). Catch of larger and older fish may be preferable to maximize yield while minimizing the number of individuals removed from the population, while also allowing fish to reproduce before capture to prevent recruitment or growth overfishing (e.g. Diekert, 2012), which has been identified as a concern for tuna fisheries (Bailey et al., 2013; Sun et al., 2019). This assumes that the catch of mature individuals is sufficiently indiscriminate to avoid harmful genetic and reproductive

output impacts of size-selective fishing (e.g. Swain, Sinclair, & Hanson, 2007). Due to the non-linear relation between maternal size and reproductive output in fishes, a catch method utilizing slot methods may be ideal (Hixon, Johnson, & Sogard, 2014), but is beyond the scope of this study. Despite this potential biological advantage of catching larger, mature individuals, local consumption of tunas is often small juveniles or poorer quality (due to lack of ice and proper post-harvest handling) large fish.

Compared to actual fishery statistics, the modelled yield by gear for the two LSF is within the bounds of reality. To maximize total fishery PR, longliners would increase their effort by 126% relative to current while purse seiners decrease their effort to 82% of current. No SSF would occur. The model estimates this would result in a yield change by gear of 223% for longliners and 93% for purse seiners. Estimating the possible total capacity of SSF is difficult due to the lack of reported data. Current effort estimates are not available, but a recent estimate of total SSF catch in the WCPO was 514,000 t (Gillett, 2011). In the maximum SR scenario, the yield by gear was therefore 99% of this value for handline and 256% for small scale surface. The model output may therefore exceed the reasonable near-future capacity of SSF, although there are a large number of efforts to develop tuna SSFs in Pacific Island countries and territories (Gillett & Tauati, 2018).

Suboptimal Model Results

One hundred and sixty thousand possible effort combinations were inputted to the model, of which 3.6×10^4 outputs were within the two model limitations of positive PR per gear and species' catches within 80% of their MSY. The optimized scenarios represent three of these. Examination of all outputs gives a more nuanced view of the trade-offs inherent in results and the balance between the three major state variables (PR, SR, and yield; Figure S1-S3). While few modelled effort combinations gave near-maximum values for PR (4% of combinations greater than 90% of max value), SR (5%), or yield (13%), there were many (26%, 29%, and 40%, respectively) possible effort combinations that gave results of c. 80% of the maximum values (Figure 4). This implies a high level of flexibility if policy makers find the effort distributions modelled to give maximum values infeasible and consider sub-optimal values acceptable, which is more likely than the extremes predicted by the optimizations.

State variables (PR, SR, yield) need to be considered simultaneously to determine the magnitude of trade-offs between objectives. PR and SR were highly correlated (Spearman's correlation: 0.91), with moderate correlations between PR and yield (0.47) and SR and yield (0.48), due to SR always being some proportion of PR, depending on the amount of subsidization. SR ranged from 66-96% of PR, with an approximately normal distribution of SR/PR, mean 81% (Figure 5). The relations between PR or SR and

yield were more complex (Figure 5, 6). For a given value of one of the state variables the values of the other two can vary greatly, especially yield. As an example, if a PR of \$3.0 billion (the approximate current value) is desirable, the 346 possible model outputs with PR within \$0.01 billion of this target have SR ranging from \$2.0 billion to \$2.9 billion and yield ranging from 0.5 MT to 2.0 MT (Figure 5, 6). This minimum yield value was achieved with all fishing effort distributed between longline and handline gears, which catch small numbers of highly valuable adult yellowfin and skipjack. The maximum yield, in contrast, had most fishing effort in the purse seine and small scale surface gears, which can catch large numbers of low value skipjack and juvenile yellowfin and bigeye. If a further goal of \$2.5 billion SR is added to the target of \$3.0 billion PR (i.e. an estimated reduction in capacity-enhancing subsidies of \$0.5 billion), yield still ranges from 0.9 MT to 1.9 MT. Despite these wide ranges, the majority of results were clustered near values of approx. PR \$3.2 billion, SR \$2.8 billion, and yield 1.7 MT (Figure 4, 5).

The top 10 outputs per major variable were extracted and the associated other two major variables and gear efforts examined (Table 5). The analysis of top 10 outputs per variable reveals the flexibility in effort combinations that give near-equal PR, SR, or yield. For example, the scenario with maximum PR essentially pushes out the entire SSF sector. However, this complete closure is extremely unrealistic, especially as SSF are critical to food and employment security. To mitigate this, moving slightly away from the optimal, for example to the sixth highest PR output, could be selected as it allows for continued effort in both handline and small-scale surface SSFs, and still maintains 99% of the maximum PR.

Sensitivity Analyses

To address the assumption that the catchability of small scale surface gears is approximately 1% of purse seine catchability, the model was rerun with the catchability coefficient (q) of small scale surface at either double or half its initial value (Table 7). If the model is optimized to maximize PR, a lower q has little impact on effort distributions, and a higher q shifts effort from purse seine to small scale surface fleets. If the model is optimized to maximize SR, a lower q results in effort being distributed between all 4 gears (rather than only the SSF), and a higher q has little impact on effort distributions. Changing the catchability coefficient had little impact on total PR, SR, or yield.

Furthermore, sensitivity analyses were conducted for doubled fishing costs of longline, handline, and small scale surface gears (Table 6). Increasing longline costs reduced the contribution of that gear's effort to the maximum PR scenario, while increasing handline and small scale surface costs removed the other's contribution to the maximum SR scenario. When both handline and small scale surface costs

were increased, the effort distributions for maximum PR and SR became identical as the low profitability of the SSF minimized their rent, prioritizing the larger gears.

Socio-Political Implications

While not an explicit exercise in management strategy evaluation (MSE), the model developed here does link fisheries management with ecological, social, and economic outcomes. For tuna, MSEs are becoming more mainstream, and in the WCPO, the need for harvest strategies are being paired with development and operationalization of an MSE framework (WCPFC, 2014, CMM 2014-06). However, as is the case with many MSEs, the current focus on predominantly ecological outcomes may not bring to light the necessity to consider other objectives (social and economic). These objectives, whether explicit or implicit, may make the assumption of cooperating being attainable unrealistic. Fishing nations and industries may have diverse objectives in continuing fishing effort, ranging from the obvious provisioning of food, employment, and income to continuation of cultural traditions or maintenance of sovereignty in remote areas without a military presence. Illegal, unreported, and unregulated fishing is an additional concern beyond the scope of this study. In this section, we highlight the socio-political implications of management strategies that would prioritize one objective over another.

The results of this study indicate that optimizing effort to maximize industry benefits (PR) or minimize subsidization (maximize SR) gives scenarios that may be socio-politically infeasible, with the potential drawbacks to their use summarized in (Table 8). Specifically, any fisheries management decision that would push out an entire fleet is likely to be met with opposition by countries at the international negotiating level, and by industry lobby groups within a country. All fishing cannot be conducted solely by LSF due to the critical importance of SSF to local livelihoods, food security, and culture; nor can all effort be in the SSF as the sector does not have the capacity and LSF fleets are well established, including an increasing proportion of domestic vessels, especially for purse seiners (Brouwer et al., 2018). While all scenarios give an ecological “win” in terms of keeping catches below 80% MSY, as mandated by model assumptions, the triple bottom line (i.e. ecological, economic, and social sustainability) is not necessarily met. The maximum yield scenario or the “sub-optimal” maximum PR or SR scenarios provide more realistic goals for policy makers in the WCPO. These also illustrate the necessity of considering multiple goals (such as PR, SR, and yield) simultaneously. That is to say that trade-offs in fisheries management are inevitable, but they can be mitigated and minimized to some degree.

Model results also highlight the importance of differential subsidization of LSF vs SSF and the difference in data availability. Current capacity-enhancing and ambiguous subsidies to the longline and purse seine fleets were estimated as a total of \$1.0 billion by this study, which is similar to the total subsidy value of \$1.5 billion estimated by Sumaila et. al for the WCPO (2014). This study's subsidy estimate increased to \$1.4 billion when efforts were optimized to maximize PR, but was only \$0.2 billion when all effort was in the SSF to maximize SR. The lack of data collected and reported for SSF (despite laudable efforts by R. Gillett; see his multiple works cited in the reference list) precluded this study from a more nuanced view of variability in this sector. As demonstrated in the sensitivity analysis, increases in SSF fishing costs can shift the model results with effort optimized to maximize PR and SR away from SSF gears' efforts. Conversely, if SSF costs are in fact much lower than the modelled value (expert estimates were as low as under \$10 per day) this would of course shift both rent-optimized scenarios towards all effort in the SSF gears. Despite increasing attention to data poor fisheries, and to the small-scale sector, the lack of 'data equity' that exists between LSF and SSF sectors is not trivial from a fisheries management perspective. Fisheries management in many places, and certainly in the context of RFMOs, will only update knowledge based on quantitative data sources (WCPFC, 2000). Management decisions get made based on data, of which there is disproportionately more for LSF sector, and additionally, continued subsidization of LSF further enables lobbying for those beneficial (to LSF) decisions at RFMO meetings (Petersson, Dellmuth, Merrie, & Österblom, 2019). It is worth noting that some amount of capacity enhancing subsidization may be valid, for example to develop underdeveloped fisheries, to shift effort from one area to another, or to prioritize a sector of importance in order to provide socio-economic benefits (i.e., a net gain).

The variable which varied the most widely between scenarios was the estimated number of direct fishing jobs generated by effort combination. LSF employ far fewer people per unit catch than SSF by a factor of about 24 (Chuenpagdee et al., 2006; FAO, 2012; Jacquet & Pauly, 2008). This has implications not only for employment opportunities in remote or rural areas where SSF may be a dominant employment, but also safety at sea. Commercial fishing is one of the most dangerous occupations in the world. Occupational health and safety risks in SSF are less well described and vessels are usually unregulated (Remolà & Gudmundsson, 2018), including in Pacific Islands (Gillett, 2003), though efforts to prevent injuries and fatalities are on the rise such as through the Chennai declaration signed by south and southeast Asian nations (2001). The difference in relative risks of LSF vs SSF is thus poorly understood, though the authors suggest that since SSF vessels generally make day trips and stay

623 near shore they may have lesser risks per fisher such as poor weather, navigational error, and isolation
624 than offshore LSF vessels making long trips.

625 The distribution of fishing effort between gears has ecological as well as social implications, such as
626 the lack of discarded bycatch by SSF or differential fuel usage between gears. Discarded bycatch in
627 pelagic longline and purse seine tuna fisheries includes non-target tuna, sharks, rays, seabirds, sea
628 turtles and marine mammals, and can be a primary mortality source for some of those species'
629 populations (Gilman, 2011; Hall & Roman, 2013). Meanwhile, SSF have few to no discards as all catch
630 has economic or food value. Furthermore, catch may be up to 100% tuna or tuna-like fish (Gillett, 2011),
631 minimizing catch of ecologically sensitive species. Longliners have the greatest fuel usage per tonne of
632 catch, about twice that of SSF, which are themselves about twice that of purse seiners (Gillett, 2009).
633 This fuel usage not only contributes to global climate change but also makes fishers vulnerable to
634 externalities resulting from fluctuations in global oil prices (Parker, Vázquez-Rowe, & Tyedmers, 2015;
635 Tyedmers & Parker, 2012). SSF are the most financially vulnerable to these cost fluctuations and have
636 been found to reduce distances travelled and alter gear type when fuel costs increased (Gillett, 2009).

637 A shift towards greater catch by SSF relative to LSF to prioritize SR, yield, and the socio-cultural
638 implications of SSF to WCPO nations would be a shift towards more small, nearshore vessels. Beyond
639 the potential implications for safety, this would greatly reduce fishing efforts in offshore waters
640 including high seas pockets. Closure of or reduced fishing in the high seas has been suggested in recent
641 years, with suggested benefits including increased global profits, yields, and stock conservation (White &
642 Costello, 2014) while decreasing inequality in maritime countries (Sumaila et al., 2015), increasing EEZ
643 catches and coastal community resilience to climate change (Cheung et al., 2016), and negligibly
644 affecting food security (Schiller et al., 2018). Despite these proposed benefits, high sea closures are
645 politically contentious and require high levels of international cooperation and monitoring. If the results
646 of this study are broadly applicable to other fisheries with both LSF and SSF it may indicate that shifting
647 effort into SSF would not only accrue multiple benefits to the fishery and local citizens but also de facto
648 close offshore and high seas waters to fishing activity without requiring explicit domestic or
649 international legislation to that goal.

650 Our model did not have a spatial dimension so we were not able to consider the future impacts of
651 climate change on WCPO tuna from changes in oceanographical conditions, including temperature,
652 dissolved oxygen, and primary productivity projected to impact population dynamics and movement
653 patterns. Declines in primary productivity influenced by temperature changes in the western equatorial

WCPO are projected to cause eastward shifts in tuna distributions, especially skipjack and yellowfin (Lehodey et al., 2017; Lehodey, Senina, Calmettes, Hampton, & Nicol, 2013; Senina et al., 2018), which will then be vulnerable to declines in oxygen in the eastern equatorial WCPO (Schmidtke, Stramma, & Visbeck, 2017) as they have low tolerance (Senina et al., 2018; Stramma et al., 2012). This eastern shift could cause substantial catch reductions to fleets in western countries such as Indonesia and the Philippines, where most SSF tuna fishing occurs (Gillett, 2009). Domestic fleets of these and Pacific Island nations may need to move with the tuna, potentially resulting in novel access fees to relocate to other nations' EEZs (McIlgorm, 2010). This study's model is poorly equipped to forecast these changes due to the assumption of spatial mixing. Demand for tuna may increase as non-tuna fished species will also be impacted by climate change, harming coastal subsistence fisheries e.g. coral reef fish (Gillett, 2009). Climate change is further expected to adversely impact physical infrastructure, food systems, and health in Pacific Island nations to a degree that may be considered dangerous (Barnett, 2011; Hanich et al., 2018). Sea level rise risks submerging crucial coastal infrastructure for domestic vessels, potentially requiring large scale investment (i.e., potential subsidies) to allow for fishing to continue. This underscores the importance of gathering data and modelling features of SSF in the region to quantify the role of these fisheries and make informed policy decisions. This study contributes to this discussion of barriers facing effective management of SSF by highlighting the role of capacity-enhancing subsidies and the lack of data equity between the WCPO LSF and SSF.

Conclusion

The dynamic externality of the equatorial WCPO tuna fishery at the gear level makes it a prime candidate for examination via the lens of bioeconomic game theoretic modelling. As one of the largest fisheries in the world with catch by both socially-crucial SSF and highly profitable LSF, its management has wide-ranging implications locally and globally. WCPO tuna fisheries management must look beyond biological sustainability objectives to socio-economic goal setting, especially considering the disproportionate benefits of capacity enhancing subsidies to LSF. This study quantitatively demonstrates major trade-offs implicit in this management including the catch of low value skipjack and juvenile yellowfin and bigeye for maximum food supply vs catch of high value adult yellowfin and bigeye for export to the luxury market; and the catch of these species by LSF for the greatest potential industry benefit with fewer workers vs by SSF for the greatest potential social benefits. The latter of these is likely to be broadly applicable to all fisheries with small- and large-scale components. These trade-offs must be considered explicitly to best provide social, economic, and ecological benefits from this

important transboundary fishery. Notably, this work argues for the inclusion of explicit social objectives in fisheries management, such that decision-making among possible trade-offs can be made in a way that best meets multiple objectives. This would help countries jointly decide on the future of their fisheries, in terms of the distribution of effort and of benefits.

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Data Availability Statement

Input data and parameters used in the model are available in Tables 1-3. The model script and output file are available on GitHub (Willis & Bailey, 2019).

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980 Tables

981 Table 1 Biological and fishing parameters and values used for WCPO skipjack tuna. Gears are longline

982 (LL), purse seine (PS), handline (HL), and small scale surface (SSS).

		Value	Source
Biological			
L_{∞}	Mean asymptotic length (cm)	106	Molony (2008) (average)

A	Maximum age (years)	5	McKechnie et al. (2016)
W_m	Weight at maturity (kg)	1.56	Langley, Hampton, & Ogura (2005)
a	Length-weight relationship	8.6388E-06	Langley & Hampton (2008)
b	Length-weight relationship	3.2174	Langley & Hampton (2008)
K	Growth coefficient	0.3105	Molony (2008) (average)
κ	Recruitment compensation	36	Calculated from Langley & Hampton (2008) by Bailey et al. (2013)
Fishing			
q^g (LL, PS, HL, SSS)	Catchabilities	0, 3.571E-6, 0, 3.571E-8	Calculated from Brouwer et al (2018), SPC-OFP (2018), Williams & Reid (2018)
p (LL, PS, HL, SSS)	Ex-vessel price (USD/t)	0, 1600, 0, 1300	Sea Around Us, Williams & Reid (2018)
λ^g (LL, PS, HL, SSS)	Subsidy intensity	0.2105, 0.2139, 0.0266, 0.0266	LL and PS calculated from Sea Around Us data (Sumaila et al., 2010); HL and SSS derived using Schuhbauer et al. (2017)
MSY	Maximum sustainable yield (t/year)	1891600	Brouwer et al. (2018)

983

984 Table 2 Biological and fishing parameters and values used for WCPO yellowfin tuna. Gears are longline
 985 (LL), purse seine (PS), handline (HL), and small scale surface (SSS).

		Value	Source
Biological			
L_∞	Mean asymptotic length	175	Molony (2008) (average)

	(cm)		
A	Maximum age (years)	6	Tremblay-Boyer et al. (2017)
W_m	Weight at maturity (kg)	19	Molony (2008)
a	Length-weight relationship	2.15E-05	Langley et al. (2009)
b	Length-weight relationship	2.9369	Langley et al. (2009)
K	Growth coefficient	0.3920	Molony (2008) (average)
κ	Recruitment compensation	12	Calculated from Langley et al. (2009) by Bailey et al. (2013)
Fishing			
q^g (LL, PS, HL, SSS)	Catchabilities	2.100E-10, 1.615E-6, 1.212E-8, 8.077E-9	Calculated from Brouwer et al (2018), SPC-OFP (2018), Williams & Reid (2018)
p (LL, PS, HL, SSS)	Ex-vessel price (USD/t)	8000, 2300, 7700, 2000	Sea Around Us, Williams & Reid (2018)
λ^g (LL, PS, HL, SSS)	Subsidy intensity	0.2882, 0.1688, 0.0260, 0.0260	LL and PS calculated from Sea Around Us data (Sumaila et al., 2010); HL and SSS derived using Schuhbauer et al. (2017)
MSY	Maximum sustainable yield (t/year)	586400	Brouwer et al. (2018)

Table 3 Biological and fishing parameters and values used for WCPO bigeye tuna. Gears are longline (LL), purse seine (PS), handline (HL), and small scale surface (SSS).

	Value	Source
Biological		

L_{∞}	Mean asymptotic length (cm)	180	Hampton (2002)
A	Maximum age (years)	7	Vincent et al. (2018)
W_m	Weight at maturity (kg)	23.47	Molony (2008)
a	Length-weight relationship	1.97E-05	Harley et al. (2009)
b	Length-weight relationship	3.0274	Harley et al. (2009)
K	Growth coefficient	0.3152	Farley et al. (2018)
κ	Recruitment compensation	12	Calculated from Harley et al. (2009) by Bailey et al. (2013)
Fishing			
q^g (LL, PS, HL, SSS)	Catchabilities	7.875E-11, 5.769E-7, 4.327E- 9, 2.885E-9	Calculated from Brouwer et al (2018), SPC-OFP (2018), Williams & Reid (2018)
p (LL, PS, HL, SSS)	Ex-vessel price (USD/t)	11000, 2600, 10700, 2300	Sea Around Us, Williams & Reid (2018)
λ^g (LL, PS, HL, SSS)	Subsidy intensity	0.2745, 0.1924, 0.0273, 0.0273	LL and PS calculated from Sea Around Us data (Sumaila et al., 2010); HL and SSS derived using Schuhbauer et al. (2017)
MSY	Maximum sustainable yield (t/year)	159020	Brouwer et al. (2018)

Table 4 Optimized efforts of longline (LL), purse seine (PS), handline (HL), and small scale surface (SSS) gears of the equatorial WCPO tuna fishery to maximise private rent, social rent, or total yield. For LL and PS the effort is additionally given as a percent (%) of current effort. LL effort is given in hooks/year, all

993 other gears in days/year. The total yield by scenario is given both in tonnes and as a percent of MSY for
 994 that species.

	Max PR	Max SR	Max Yield
Efforts			
LL (% current)	5.05E+08 (133%)	1 (0%)	9.47E+07 (23%)
PS	4.26E+04 (68%)	1 (0%)	1.89E+04 (36%)
HL	1	1.70E+07	6.32E+06
SSS	1	7.37E+06	6.32E+06
Total PR (billion \$)	4.38	3.61	3.66
Total SR (billion \$)	2.96	3.45	3.17
Total jobs	6.48E+04	2.74E+07	2.06E+07
Total yield (MT)	2.05	1.83	2.11
Skipjack (% MSY)	1.47E+06 (77%)	1.24E+06 (65%)	1.51E+06 (79%)
Yellowfin	4.53E+05 (77%)	4.61E+05 (78%)	4.69E+05 (79%)
Bigeye	1.27E+05 (79%)	1.27E+05 (79%)	1.23E+05 (77%)

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997 Table 5 Top 10 model outputs for private rent (USD), social rent (USD), and yield (MT). The second
 998 column indicates the percent of the maximum possible output of interest (i.e., PR, SR, or yield), with
 999 corresponding outputs of competing objectives and gear (longline, purse seine, handline, small scale
 1000 surface) efforts in subsequent columns. For each column section the minimum value per section is in
 1001 italics and the maximum in bold. Longline efforts were measured in hooks/year, all other gears in
 1002 days/year.

Highest PR outputs		PR (billion \$)	SR (billion \$)	Yield (MT)	LL	PS	HL	SSS
1	100%	4.38	2.96	2.05	5.05E+08	4.26E+04	<i>1</i>	<i>1</i>
2	99%	4.33	2.93	1.98	5.05E+08	4.03E+04	<i>1</i>	<i>1</i>
3	99%	4.33	2.94	2.04	5.05E+08	4.03E+04	<i>1</i>	5.26E+05
4	99%	4.33	2.97	1.92	5.37E+08	<i>3.32E+04</i>	<i>1</i>	1.05E+06

5	99%	4.32	2.97	1.99	4.74E+08	4.03E+04	1.00E+06	1
6	99%	4.32	2.98	2.05	4.74E+08	4.03E+04	1.00E+06	5.26E+05
7	99%	4.32	2.94	1.86	5.37E+08	3.32E+04	1	5.26E+05
8	99%	4.32	3.01	2.00	4.42E+08	4.03E+04	2.00E+06	1
9	98%	4.31	2.92	1.79	5.37E+08	3.32E+04	1	1
10	98%	4.30	2.96	1.80	5.05E+08	3.32E+04	1.00E+06	1

Highest SR outputs

1	100%	3.61	3.45	1.83	1	1	1.70E+07	7.37E+06
2	100%	3.60	3.44	1.77	1	1	1.70E+07	6.84E+06
3	100%	3.62	3.44	1.72	1	2.37E+03	1.70E+07	5.79E+06
4	99%	3.58	3.43	1.71	1	1	1.70E+07	6.32E+06
5	99%	3.64	3.42	1.66	1	4.74E+03	1.70E+07	4.74E+06
6	99%	3.66	3.42	1.83	3.16E+07	2.37E+03	1.60E+07	6.84E+06
7	99%	3.60	3.41	1.66	1	2.37E+03	1.70E+07	5.26E+06
8	99%	3.62	3.41	1.87	3.16E+07	1	1.60E+07	7.89E+06
9	99%	3.64	3.41	1.77	3.16E+07	2.37E+03	1.60E+07	6.32E+06
10	99%	3.62	3.41	1.82	3.16E+07	1	1.60E+07	7.37E+06

Highest Yield outputs

1	100%	3.66	3.17	2.11	9.47E+07	1.89E+04	1.20E+07	6.32E+06
2	100%	4.10	3.04	2.10	3.16E+08	3.79E+04	5.00E+06	1.58E+06
3	100%	3.50	3.24	2.10	3.16E+07	4.74E+03	1.50E+07	1.00E+07
4	100%	4.05	3.06	2.10	2.84E+08	3.55E+04	6.00E+06	2.11E+06
5	100%	3.83	3.14	2.10	2.21E+08	1.89E+04	9.00E+06	6.32E+06
6	100%	3.72	3.22	2.10	1.26E+08	1.42E+04	1.20E+07	7.37E+06
7	100%	3.67	3.13	2.10	1.26E+08	1.89E+04	1.10E+07	6.32E+06
8	99%	3.52	3.12	2.09	3.16E+07	1.89E+04	1.30E+07	6.32E+06
9	99%	4.11	3.00	2.09	3.47E+08	3.79E+04	4.00E+06	1.58E+06
10	99%	3.78	3.17	2.09	1.89E+08	1.66E+04	1.00E+07	6.84E+06

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Table 6 Cost sensitivity analysis results for longline (LL), handline (HL), and small scale surface (SSS) gears. The main model's costs were \$1/hook, \$100/day, and \$100/day, respectively. Total private rent (USD), social rent (USD), and yield (MT) across all gears and species is given for each scenario. Longline efforts were measured in hooks/year, all other gears in days/year.

Max PR	Main model	LL \$2	HL \$200	SSS \$200	HL & SSS \$200
Efforts					
LL	5.05E+08	4.42E+08	5.05E+08	5.05E+08	5.05E+08
PS	4.26E+04	4.03E+04	4.26E+04	4.26E+04	4.26E+04
HL	1	2.00E+06	1	1	1
SSS	1	1	1	1	1
PR (billion \$)	4.38	3.88	4.38	4.38	4.38
SR (billion \$)	2.96	2.56	2.96	2.96	2.96
Yield (MT)	2.05	2.00	2.05	2.05	2.05
Max SR					
Efforts					
LL	1	1	1.58E+08	6.00E+08	5.05E+08
PS	1	1	1.89E+04	7.11E+03	4.26E+04
HL	1.70E+07	1.70E+07	1.20E+07	1	1
SSS	7.37E+06	7.37E+06	1	6.32E+06	1
PR (billion \$)	3.61	3.61	3.78	4.16	4.38
SR (billion \$)	3.45	3.45	3.11	3.02	2.96
Yield (MT)	1.83	1.83	1.39	1.81	2.05
Max Yield					
Efforts					
LL	9.47E+07	9.47E+07	9.47E+07	9.47E+07	9.47E+07
PS	1.89E+04	1.89E+04	1.89E+04	1.89E+04	1.89E+04
HL	1.20E+07	1.20E+07	1.20E+07	1.20E+07	1.20E+07
SSS	6.32E+06	6.32E+06	6.32E+06	6.32E+06	6.32E+06
PR	3.66E+09	3.57E+09	3.03E+09	2.46E+09	1.83E+09
SR	3.17E+09	3.07E+09	2.54E+09	1.97E+09	1.34E+09
Yield	2.11E+06	2.11E+06	2.11E+06	2.11E+06	2.11E+06

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1012 Table 7 Sensitivity analysis results for small scale surface (SSS) catchability (q) when halved or doubled.

1013 Total private rent (USD), social rent (USD), and yield (MT) across all gears and species is given for each

1014 scenario. Longline efforts were measured in hooks/year, all other gears in days/year.

Max PR	Main model	SSS q *0.5	SSS q*2
Effort			
LL	5.05E+08	5.05E+08	6.00E+08
PS	4.26E+04	4.26E+04	1
HL	1	1	1
SSS	1	1	4.74E+06
PR (billion \$)	4.38	4.38	4.52
SR (billion \$)	2.96	2.96	3.46
Yield (MT)	2.05	2.05	1.91
Max SR			
Effort			
LL	1	1.58E+08	1
PS	1	1.89E+04	1
HL	1.70E+07	1.20E+07	1.70E+07
SSS	7.37E+06	5.26E+05	3.68E+06
PR (billion \$)	3.61	3.78	3.98
SR (billion \$)	3.45	3.11	3.82
Yield (MT)	1.83	1.44	1.83
Max Yield			
Effort			
LL	9.47E+07	3.16E+08	9.47E+07
PS	1.89E+04	3.79E+04	1.89E+04
HL	1.20E+07	5.00E+06	1.20E+07
SSS	6.32E+06	3.16E+06	3.16E+06

PR (billion \$)	3.66	3.95	3.98
SR (billion \$)	3.17	2.88	3.49
Yield (MT)	2.11	2.10	2.11

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1016 Table 8 Advantages and disadvantages of the effort optimized scenarios that maximized private rent,
 1017 social rent, or yield in the equatorial WCPO tuna fishery.

	Advantage	Disadvantage
Max PR	<ul style="list-style-type: none"> • Greatest industry profit • Best data recording and reporting 	<ul style="list-style-type: none"> • \$1.4 billion in capacity-enhancing subsidies • Few, high risk jobs • No catch remaining for SSF, risking employment and food security
Max SR	<ul style="list-style-type: none"> • Greatest social benefit in terms of social rent and employment in the small scale sector • Few to no discards • Oldest average age of yellowfin and bigeye catch allows for greatest reproductive potential 	<ul style="list-style-type: none"> • Unlikely that SSF have this much capacity or infrastructure to access the global market • May not be spatially feasible due to coastal nature of small scale fleets • Lowest average age of skipjack catch • Unrealistic that LSF would completely cease fishing
Max Yield	<ul style="list-style-type: none"> • Most even distribution of effort between large- and small-scale gears 	<ul style="list-style-type: none"> • Unlikely that LSF would reduce their effort to 23-36% of current

1018

1019 Figure legends

1020 Figure 1 Age (years) specific vulnerabilities of equatorial WCPO tunas to longline (LL), purse seine (PS),
 1021 handline (HL), and small scale surface (SSS) gears. (Figure appears in colour in the online version only).

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Figure 2 Rents and catch distribution if fishing effort in the equatorial WCPO is optimized over gears to maximize private rent (PR), social rent (SR), or yield. Gears are longline (LL), purse seine (PS), handline (HL), and small scale surface (SSS); species are skipjack (SJ), yellowfin (YF), and bigeye (BE) tunas. (Figure appears in colour in the online version only).

Figure 3 Modelled output of tuna catch in the equatorial WCPO by age (years) by longline (LL), purse seine (PS), handline (HL), and small scale surface (SSS) gears at efforts optimized to maximize private rent (PR), social rent (SR), or yield. (Figure appears in colour in the online version only).

Figure 4 Histograms of model outputted values for private rent (USD), social rent (USD), and yield (t).

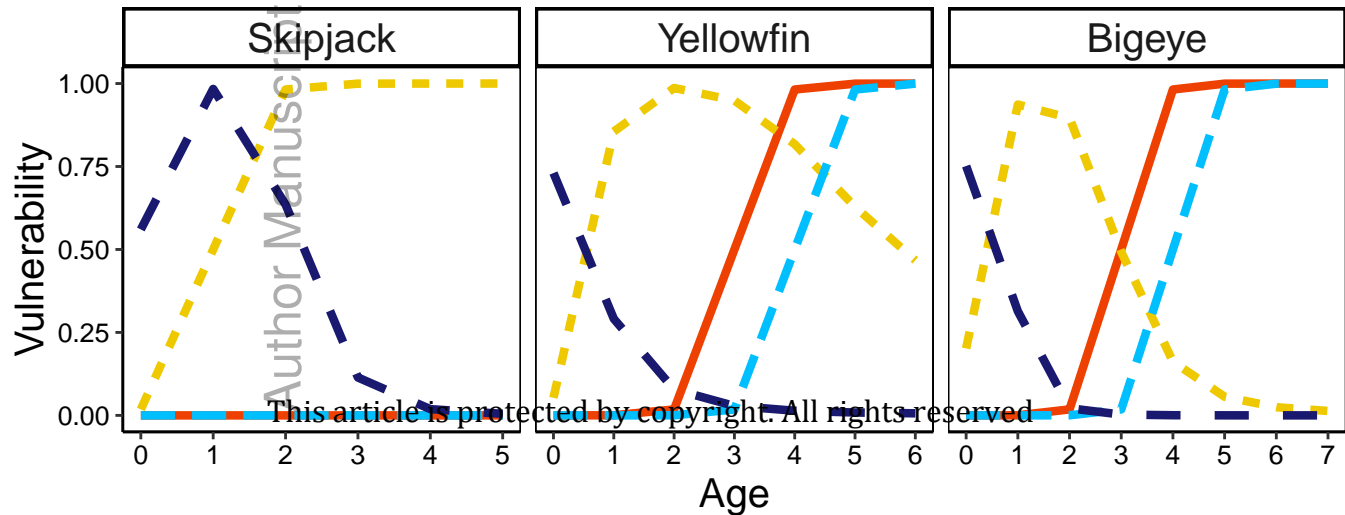
Figure 5 Two dimensional histograms of private rent (USD), social rent (USD), and yield (t) values over all model runs. Colour indicates frequency of occurrence of a particular rent-rent or rent-yield combination. For the PR vs SR plot a 1:1 line (dashed) and linear regression with intercept zero (solid; $\text{adj. } R^2 = 0.99$) are included. The step between bins is approx. $\$1.4 \times 10^8$ for PR, $\$1.1 \times 10^8$ for SR, and 7.0×10^4 t for yield. (Figure appears in colour in the online version only).

Figure 6 Three dimensional model output of all possible outputs' private rent (USD), social rent (USD), and yield (t). (Figure appears in colour in the online version only).

Supplemental Figure S1 All model outcomes for a coarser resolution version of the model with 10 possible efforts per gears' effort, as the full output (20 possible efforts) is too large to easily view. Trends were the same. All efforts are in days/year except longline (hooks/year). Rows of the figure are handline effort (1 day/year, 2111112 days/year, etc.) and columns are small scale surface effort. Within each of these HL and SSS surface combination boxes all of the possible combinations of longline and purse seine efforts are shown. Colour indicates resulting private rent (USD). The maximum private rent is circled. Effort combinations which exceeded model constraints are not shown.

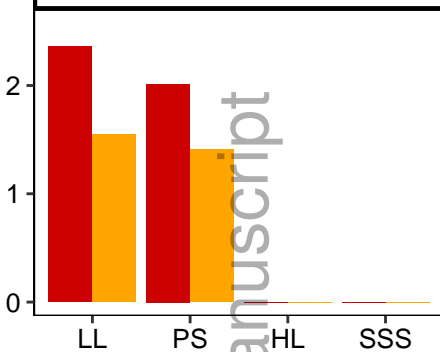
Supplemental Figure S2 All model outcomes for a coarser resolution version of the model with 10 possible efforts per gear's effort, as the full output (20 possible efforts) is too large to easily view. Trends were the same. All efforts are in days/year except longline (hooks/year). Rows of the figure are handline effort (1 day/year, 2111112 days/year, etc.) and columns are small scale surface effort. Within each of these HL and SSS surface combination boxes all of the possible combinations of longline and purse seine efforts are shown. Colour indicates resulting social rent (USD). The maximum social rent is circled. Effort combinations which exceeded model constraints are not shown.

Supplemental Figure S3 All model outcomes for a coarser resolution version of the model with 10 possible efforts per gear's effort, as the full output (20 possible efforts) is too large to easily view. Trends were the same. All efforts are in days/year except longline (hooks/year). Rows of the figure are handline effort (1 day/year, 2111112 days/year, etc.) and columns are small scale surface effort. Within each of these HL and SSS surface combination boxes all of the possible combinations of longline and purse seine efforts are shown. Colour indicates resulting yield (t). The maximum yield is circled. Effort combinations which exceeded model constraints are not shown.

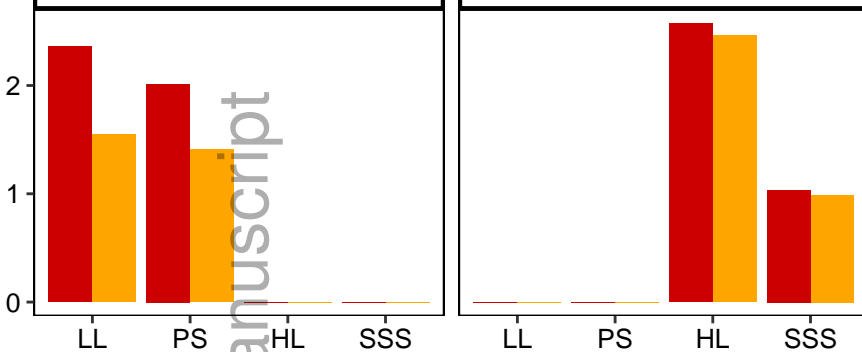


Rent (billion \$)

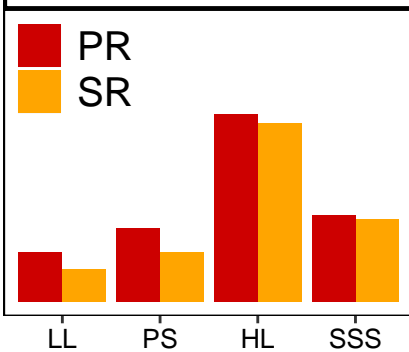
Max PR



Max SR

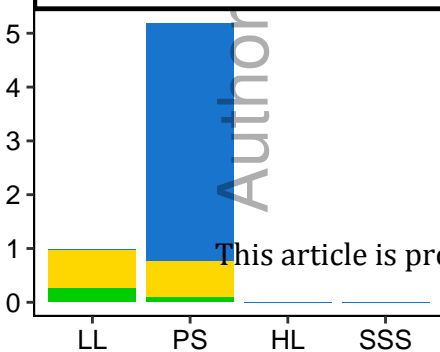


Max Yield

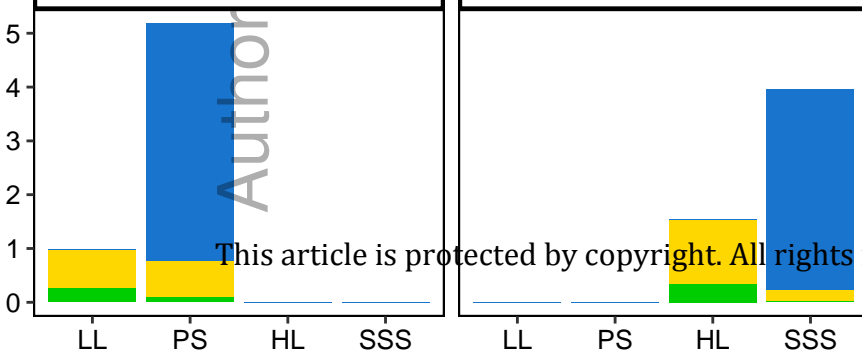


Catch (MT)

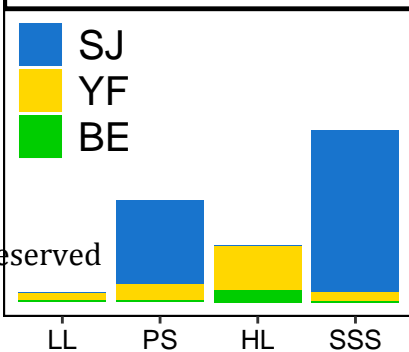
Max PR



Max SR



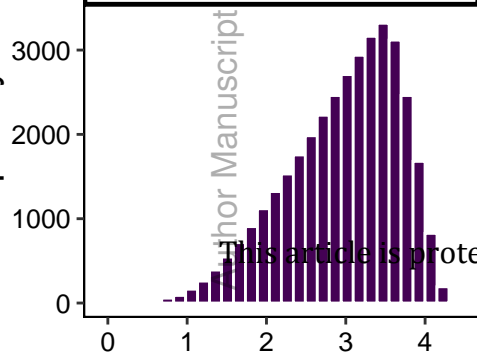
Max Yield



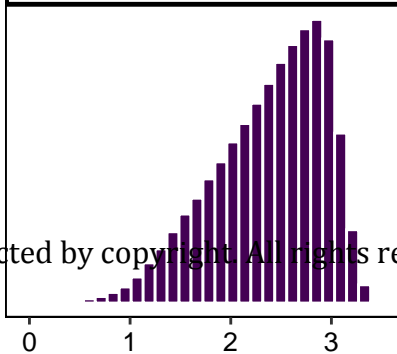
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Frequency

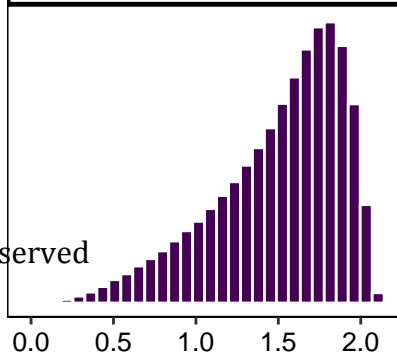
PR (billion \$)

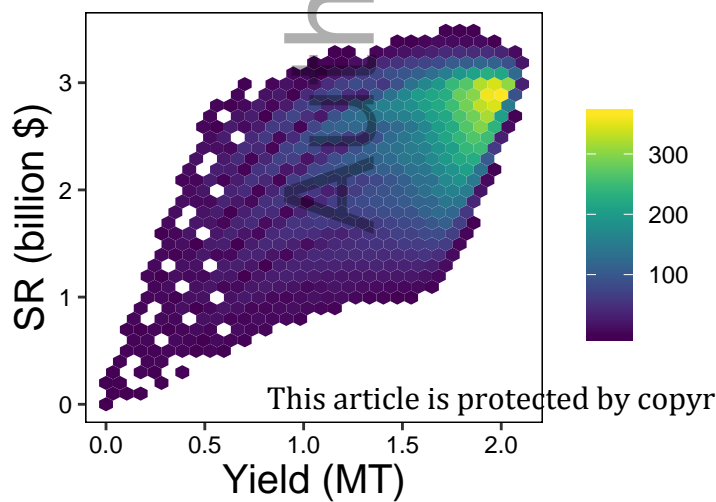
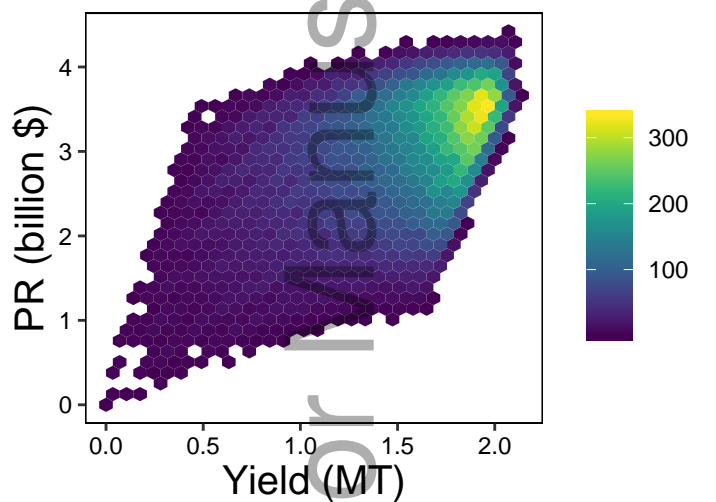
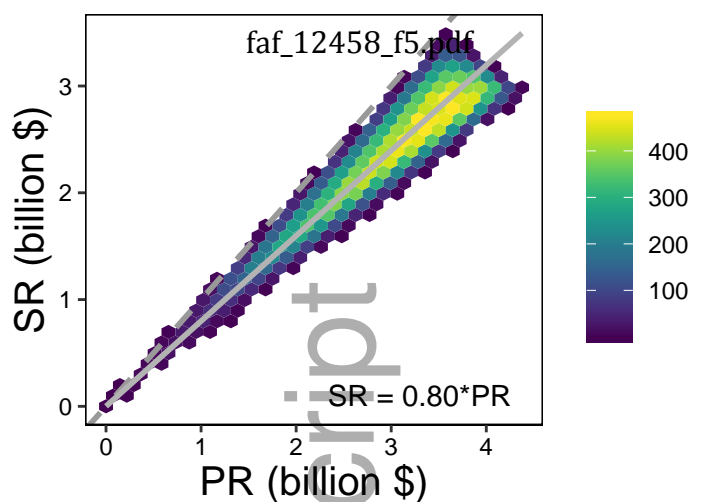


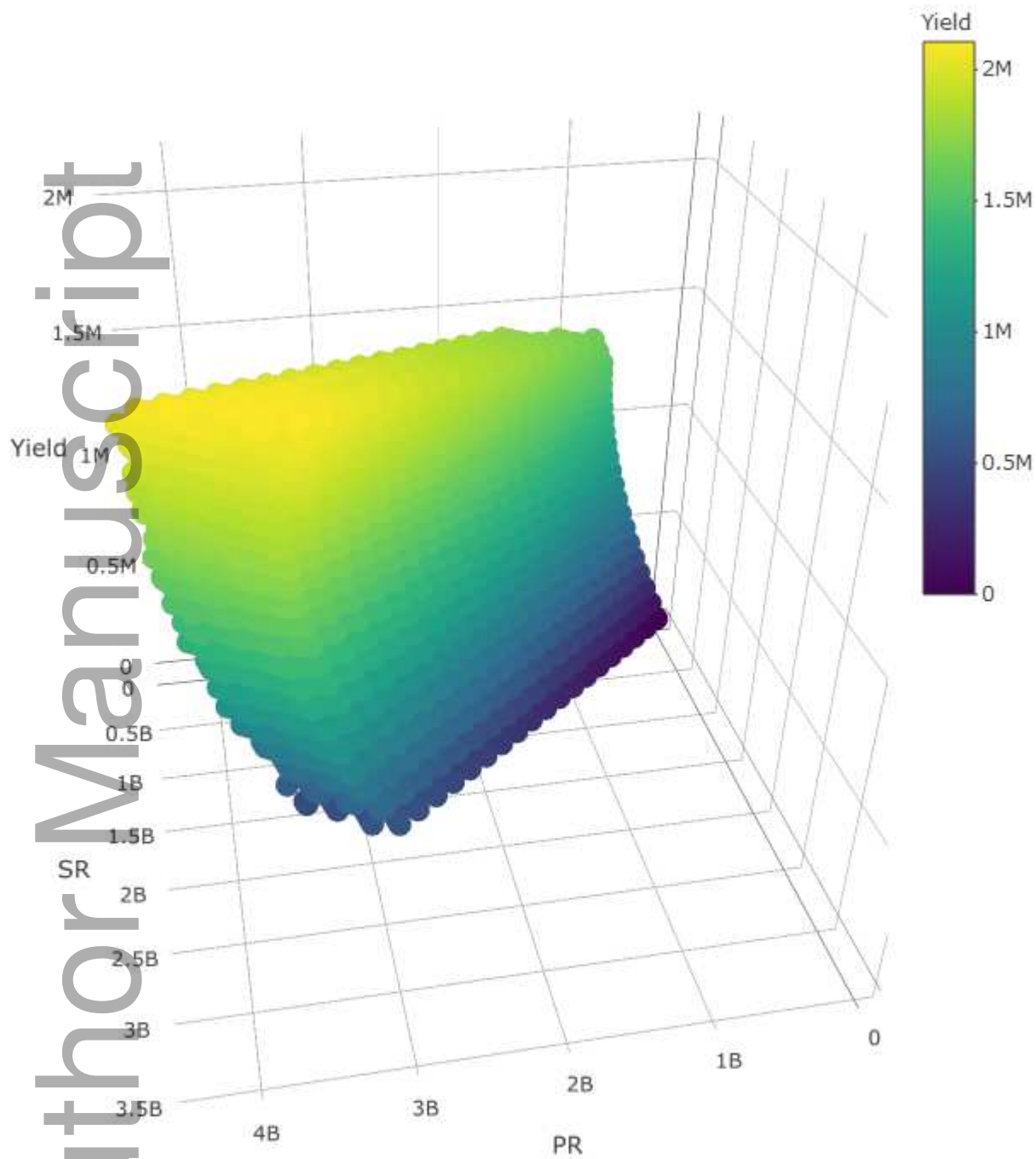
PR (billion \$)



Yield (MT)







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