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South Atlantic Natural Capital Project: Adding value to Falkland Island fisheries through the collective management of shared fish stocks.

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Closing the gap: Adding value to Falkland Island fisheries through the collective management of shared fish stocks

REPORT COMMISSIONED BY SAERI NATURAL CAPITAL PROJECT

MICHAEL HARTE AND JAMES WATSON

Closing the gap: Adding value to Falkland Island fisheries through the collective management of shared fish stocks

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Executive summary: Closing the gap: Adding value to Falkland Island fisheries through the collective management of shared fish stocks

The Southwest Atlantic is home to some of the most productive fisheries in the world. This rich natural capital underpins a dynamic, thriving economy and society in the Falkland Islands, supports coastal communities in South America and contributes to vibrant seafood markets in Asia and Europe. Yet the future of these fisheries is far from assured and the region lags behind all but the worst regional performers in terms of the percentage of fish stocks managed at sustainable levels.

Fishing is the Falkland Islands largest economic sector, accounting for 39.4% in 2015 and 58.5% of GDP in 2016. The Falkland Islands Government (FIG) receives revenue from quota fees and from company taxation paid by fishing companies and from taxes and fees by the wider maritime service sector and their employees. Given the importance of fishing to the Falklands Island economy and to FIG revenue, it is vital that the sector remains profitable and is sustainably managed.

Complicating management by Falkland Island fishing authorities, Illex and finfish fisheries target shared stocks where the total level of harvest is beyond the control of the Falkland Islands. The Southwest Atlantic is the only major fishing region of the world not to have some coordinated international fisheries management among flag States fishing in the region under the auspices of a Regional Fisheries Management Organization (RFMO).

Given the situation described, this research asks:
- What are the benefits of an effective regional fisheries management agreement for straddling stocks, such as hoki, Illex squid and southern blue whiting; and
- How would this have enhanced the Falkland Islands and regional fisheries in economic and biological terms?

To quantify the benefit of cooperation between Argentinian and Falklands fishing fleets we have developed a bioeconomic model. This model explicitly accounts for several factors:
- The profits of the South American, Falkland Island and high seas (where applicable) fleets,
- The impact of the distant water fleet on stocks in South American and Falkland Islands waters and
- The population connectivity between South American waters and Falkland Islands waters by stock movement.

With these factors in the model, we are able to define various solution concepts, specifically we compare the non-cooperative, and fully-cooperative solutions.

The following tables show the change in fishing effort, stock abundance and fleet profit by moving from a non-cooperative to cooperative model solution for South American and Falkland Islands waters as estimated by our model. The results are shown as a multiplier. A number greater than one is an increase in fishing efforts, stock abundance or profits and a number less than one is a decrease in effort, abundance or profits.

Fishing effort multipliers arising from cooperation

Fishery	South American waters effort multiplier	Falkland Islands waters effort multiplier
Hoki	0.94	0.36
Southern blue whiting	0.72	0.74
Illex	0.93	0.91

Abundance multipliers arising from cooperation

Fishery	South American waters abundance multiplier	Falkland Islands waters abundance multiplier
Hoki	1.16	1.43
Southern blue whiting	1.27	1.31
Illex	1.02	1.03

Profit multipliers arising from cooperation

Fishery	South American waters profit multiplier	Falkland Islands waters profit multiplier
Hoki	1.19	3.35
Southern blue whiting	1.06	0.15
Illex	1.00	1.48

The results show that the cooperative solution is always superior to non-cooperative solution in aggregate, leading to better overall economic and biological outcomes. Aggregate profits are higher, fishing effort is lower, stock abundance is greater, and, by inference, broader ecosystem services should increase in quality and quantity. Nevertheless, it is evident that the distribution of economic and ecological benefits depends on relative prices, costs and fisheries connectivity between South American and Falkland Islands waters and in the case of Illex, the high seas. Depending on the fishery (or the specification of the fishery) sometimes the Falkland Islands benefits most, sometimes South America benefits most. Sometimes, as in the case of the southern blue whiting fishery, one country may actually be worse off even though the aggregate result is superior to the non-cooperative solution. We note that there is uncertainty about the fishery valuation data for southern blue whiting which may lead to an overly pessimistic estimate of the change in profits for the Falkland Islands fishery.

Unequal benefits and costs lead to differing incentives and disincentives to cooperate. For two or more parties to cooperate;

- They must both be better off cooperating than not cooperating and feel cooperation results in a fair and equitable outcome.
- They must be sure that the other party will cooperate and continue to cooperate.
- They must be certain that no third party can come in and enjoy the benefits of their cooperation at their expense.

It is unclear from the preceding analysis that these conditions hold in the Southwest Atlantic. In the absence of financial mechanisms (called side payments) to compensate each territory (and its fishers), depending on the fishery they may not be better off cooperating than not cooperating and they are unlikely to feel cooperation is resulting in a fair and equitable outcome. Highly variable catches due to environmental variability and longer-term changes in stock abundance and distribution due to climate change further complicates the identification and distribution of benefits from cooperation.

Finally, in the case of Illex, the absence of an RFMO in the Southwest Atlantic means that bi-lateral cooperation could be undermined by third parties. Cooperation between South American countries and the United Kingdom/Falkland Islands would not prevent distant water fishing fleets (for example from China, Spain, Taiwan and South Korea) fishing on the high seas. Having no obligation to regulate their catches, or even report their catch, these vessels will limit the economic and ecological benefits of bilateral cooperation between coastal States in the region. At the same time, the potential ecological and economic impact of these third-party free riders could provide the impetus for efforts between coastal States to establish an RFMO.

There are at least three scenarios for the future of shared Southwest Atlantic fisheries:

- The status quo: Coastal States in the Southwest Atlantic continue myopic non-cooperative fishing strategies, and high seas fishing by distant water fleets increases in intensity. In this scenario, shared fish stocks continue to decline in abundance and too much aggregate effort in the fisheries leads to falling profits and economic losses for all fishery participants. The Falkland Islands do not have a sufficient share of regional harvests to place any real pressure on stock abundance in South American waters, while South American States' fishing behaviour can impact stock abundance in Falkland Island waters. Over time, the Illex fishery shows a downward trend in stock abundance and profitability as unregulated high seas fisheries severely reduces spawning biomass in low abundance years.

- Modified status quo: The United Kingdom and Argentina cooperate on joint research initaitives and agree to coordinate actions over the setting and enforcement of total allowable catches in shared fisheries. Declines in finfish stock abundance slows but rebuilding is slow, and the Falkland Islands remain dependent on significant changes in capacity and management practices in Argentine fisheries for the health of their finfish fisheries. The Illex fishery continues to show a downward trend in stock abundance and profitability due to continued unregulated high seas fishing.

- Enhanced international cooperation: Under this scenario Southwest Atlantic coastal States agree to, and enforce, hard catch limits and shared rebuilding strategies for overfished finfish stocks across EEZs and fleets. An RFMO consisting of coastal States and the flag States of distant water fishing fleets is established that begins to put in place conservation management measures that further scaffold coastal State rebuilding strategies for finfish and begin to regulate and institute monitoring, control and enforcement for high seas fishing effort for Illex. Regional fisheries management meets or exceeds the performance of other major global fishing regions.

The creation of an RFMO would still need many years for agreement to be reached between cooperating states and for this cooperation to bring about ecological and economic improvements. A more realistic trajectory is from the status quo to a modified status quo that builds on current efforts to re-establish and strengthen the Southwest Atlantic fisheries Commission.

Whether or not substantive economic and biological benefits are forthcoming depends greatly on the political will and institutional capacity of Commission members to bring about change in their respective fisheries. Even with regional stock rebuilding and recovery of the fisheries, the economic and ecological benefits to the Falkland Islands are uncertain because of the Falkland Islands' smaller fishing effort targeting shared stocks in Falkland Island waters. In the absence of an RFMO, Argentina and the United Kingdom still have a common interest in reducing high seas fishing effort targeting Illex and could work with European and other markets to regulate and restrict the importation of unreported and unregulated Illex catch taken on the high seas.

Adding to the complexity and uncertainty of management is the impact of climate driven changes on Southwest Atlantic fisheries. Though the impact is unknown, there have been abrupt changes in catches observed during the last decade. Climate-driven changes in stock range and distribution may exacerbate ecological, economic, food and conflict-related insecurity. These conflicts will be amplified by the failure to coordinate the management of regional stocks that straddle or migrate between the waters of different countries and between exclusive economic zones and the high seas.

Both coastal and flag States in the Southwest Atlantic have good reason to cooperate to address unsustainable levels of fishing effort, illegal, unregulated and unreported fishing, and the consequences of climate change. Regional geopolitics, however, mean that enhanced bilateral and multilateral cooperation is unlikely in anything but the long-term. Even the creation of an RFMO in the medium term would need many years for agreement to reached between cooperating states and for this cooperation to bring about change. In the short to medium term two strategies seem the most likely to have the most success:

- Coordinated exchange of fisheries data, joint research cruises, joint scientific analysis, and fisheries advice to respective governments through the South Atlantic Fisheries Commission; and
- Coordinated action by Argentinian and Falkland Island Illex-based exporters aimed at eliminating the importation of unregulated and unreported high seas Illex catches by European and other key markets.

Introduction

Abundant fisheries on the Patagonian Shelf region of the Southwest Atlantic support major international fishing fleets. These fleets have been extracting up to 1 million tonnes of squid annually, consisting mostly of Argentinean squid (*Illex argentines*) and Patagonian squid (*Doryteuthis gahi*) and over 1 million tonnes of fish annually, including hakes (*Merluccius hubbsi*), hoki (*Macruronus magellanicus*), rock cod (*Patagonotothen ramsayi*) and southern blue whiting (*Micromesistius australis*).[1,2] Squid can average 50% of the landing volume and up to 60% of the landed value of catches in the Southwest Atlantic. This is by far the greatest share by squid of fisheries volume and value from any large marine ecosystem in the world.[3]

The Falkland Islands are an Overseas Territory of the United Kingdom, situated on the Patagonian Shelf of the Southwest Atlantic (Figure 1). Fishing is the Falkland Islands largest economic sector, accounting for 39.4% in 2015 and 58.5% of GDP in 2016.[4,5] The Falkland Islands Government (FIG) receives revenue from quota fees and from company taxation paid by fishing companies and from taxes and fees by the wider maritime service sector and their employees. Given the importance of fishing to the Falklands Island economy and to FIG revenue, it is vital that the sector remains profitable and is sustainably managed.

Falkland Island fisheries for Falklands calamari (*Doryteuthis gahi*) and Patagonian toothfish (*Dissostichus eleginoides*) have been managed as individually transferable quota (ITQ) fisheries since 2006, and other finfish fisheries since 2008. The Illex squid (*Illex argentines*) fishery has yet to enter the ITQ system because of the highly variable nature of the stock, a reliance on a large distant water fishing fleet to harvest the stock, and significant license fee income to the Falkland Islands Government.[6] A 2018 review of fishery management in the Falkland Islands was complementary of progress and its economic and sustainability

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[1] Arkhipkin, A., Brickle, P. and Laptikhovsky, V., 2013. Links between marine fauna and oceanic fronts on the Patagonian Shelf and Slope. *Arquipélago. Life and Marine Science*, *30*, pp.19-37.

[2] Laptikhovsky, V., Arkhipkin, A. and Brickle, P. (2013). From small bycatch to main commercial species: Explosion of stocks of rock cod *Patagonotothen ramsayi* (Regan) in the Southwest Atlantic. *Fisheries Research* 147: 399 – 403.

[3] Hunsicker, M. E., Essington, T. E., Watson, R., & Sumaila, U. R. (2010). The contribution of cephalopods to global marine fisheries: can we have our squid and eat them too? *Fish and Fisheries*, *11*(4), 421-438.

[4] Falkland Islands Government. 2017. State of the Falklands Islands Economy 2017. Policy and Economic Development Unit, FIG. Avilable at: http://www.fig.gov.fk/policy/component/jdownloads/send/5-reports-and-publications/89-state-of-the-falkland-islands-economy-2017

[5] Falkland Islands Government. 2018. Falkland Islands National Accounts 2007-2016. Policy and Economic Development Unit, FIG. Avilable at http://www.fig.gov.fk/policy/component/jdownloads/send/4-statistics/119-falkland-islands-national-accounts-2007-to-2016

[6] Arkhipkin, A., Barton, J., Wallace, S. and Winter, A., 2013. Close cooperation between science, management and industry benefits sustainable exploitation of the Falkland Islands squid fisheries. *Journal of fish biology*, *83*(4), pp.905-920.

achievements.[7] However, there are few opportunities for further increase harvest volume since the major fisheries are generally considered to be fully exploited. One remaining opportunity for greater engagement by Falkland Island companies is the Illex squid fishery which is exploited by both domestic and distant water fishing fleets in the Falkland Islands Interim and Outer Conservation Zones (FICZ and FOCZs) and high seas.

Complicating management by Falkland Island fishing authorities, Illex and finfish fisheries target shared stocks where the total level of harvest is beyond the control of the Falkland Islands. In 1990, the South Atlantic Fisheries Commission (SAFC) was created to address the need for bilateral management of shared fisheries. It brought together scientists and fishery managers from Argentina, the UK and the Falkland Islands. The SAFC coordinated the exchange of fisheries data, joint research cruises, joint scientific analysis, and provided fisheries advice to respective governments. Argentina withdrew from the SAFC in 2005 in protest over the Falkland Islands introducing an Individual Transferable Quota system as part of major reforms of the fishery management system.[8] Talks between the United Kingdom and Argentinian Governments began in 2016 and continued through 2018 about the importance of data exchange on fish and squid stocks in the Southwest Atlantic and the need to re-establish the SAFC.[9] Further talks and joint research cruises are scheduled in 2019.

Without bilateral and multilateral regional fisheries cooperation for key stocks such as hakes, hoki, southern blue whiting and Illex, it is very likely shared stocks are below widely recognized management reference points such as maximum sustainable and maximum economic yields. The UN Food and Agriculture Organization (FAO) reports that in the Southwest Atlantic statistical area, 42% of the assessed stocks were fished within biologically sustainable levels, the third worst performance among the 15 major FAO statistical areas.[10] The global average for assessed stocks fished within biologically sustainable levels is 66%.[11] The Southwest Atlantic is the only major fishing region of the world not to have some coordinated international fisheries management among flag States fishing in the region under the auspices of a Regional Fisheries Management Organization (RFMO).[12] Anecdotal reports also suggest an increase in unreported high seas fishing effort in the region, putting further pressure on squid stocks. This is generally thought to be Chinese squid jiggers though some longline and trawling effort is also reported.[13]

Given the situation described, this research asks ‘what are the benefits of an effective regional fisheries management agreement for straddling stocks, such as hoki, Illex squid and

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[7] Terra Moana Ltd. 2018. Independent Review of the Individual Transferable Quota System in the Falkland Islands. Report to the Falkland Islands Government.

[8] Barton, A. J., Agnew, D. J. & Purchase, L. V. 2007. The Southwest Atlantic; achievements of bilateral management and the case for a multilateral arrangement. In Management of Shared Fish Stocks. Payne, A. I. L., O’Brien, C. M. & Rogers, S. I., eds), pp. 202 – 222. Oxford: Blackwell Publishing Ltd

[9] Falkland Islands Association (ND) Falklands/Argentina Fisheries Talks: 14-15 May 2018. https://www.fiassociation.com/article.php/994 retrieved 4 December 2018.

[10] FAO. 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals. Rome. Licence: CC BY-NC-South American 3.0 IGO.

[11] FAO. 2018 *ibid.*

[12] Villasante, S., Sumaila, R. and Antelo, M., 2014. Why cooperation is better? The gains of cooperative management of the Argentine shortfin squid fishery in South America. *Environment and development economics: essays in honour of Sir Partha Dasgupta. Oxford University Press, Oxford*, pp.270-294.

[13] Undercurrent News. Chinese vessels amass near Argentine waters ahead of squid season start https://www.undercurrentnews.com/2018/12/13/chinese-vessels-amass-near-argentine-waters-ahead-of-squid-season-start/. Accessed 12/16/2018.

southern blue whiting and how would this have enhanced the Falkland Islands and regional fisheries in economic and biological terms'?

Characteristics of shared fisheries in Falkland Islands waters

Commercial fishing around the Falklands occurs in two fishing zones (Figure 2). The Falklands Interim Conservation and Management Zone (FICZ), established by proclamation in 1986 extends 150 nautical miles from a central point between the two main islands. The Falkland Islands Outer Conservation Zone (FOCZ) was established in 1990 and extended fisheries jurisdiction to 200 nautical miles to the north, east and south of the FICZ.

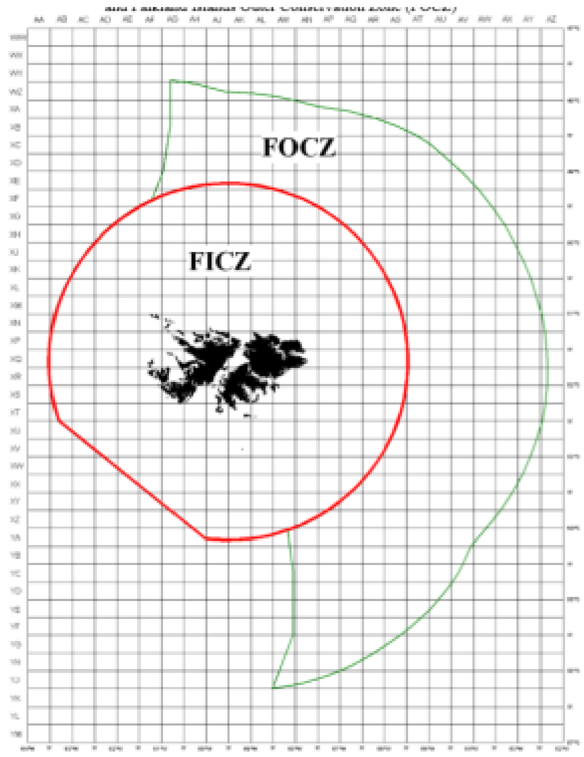

Figure 2. Map of the Falkland Islands Conservation Zones

Most of the trawl and jigging fishing activities occur on the shallower shelf areas at depths of less than 300 m targeting a range of species including hakes, southern blue whiting (*Micromesistius australis*), hoki (*Macruronus magellanicus*), and Illex (*Illex argentines*) that migrate between Argentinian and Falkland Island waters. Other fisheries for kingclip (*Genypterus blacodes*), red cod (*Salilota australis*) and rockcod (*Patagonotothen ramsayi*) may also target shared stocks, however these stocks are not generally viewed as straddling or highly migratory for management purposes.

M. hubbsi is the more common of two hake species harvested in Falkland waters.[14] Hake migrate between Argentine, Chilean and Falkland Islands waters. *M. hubbsi* is abundant in Argentine waters from November to March during the spawning season and then migrate to Falkland waters in autumn and winter months where foraging grounds are. *M. hubbsi* are caught in the northwest of the FICZ associated with the inflow of warm waters of the Argentinean Drift to the northwestern part of the Falkland Shelf. Hake are taken in the Argentine and Uruguayan EEZs in volumes that far exceed catches in Falkland Island waters (Figure 3). Recent catches in Falkland Islands waters have varied between 9,000 and 23,000 metric tonnes, representing about 3% of the total Hake catch in the SW Atlantic and from 10% to 40% of finfish catch in Falkland water, the highest proportions occurring since 2013. Southern hake (*M. australis*) is a minor bycatch in Falkland Island fisheries.[15]

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[14] Arkhipkin, A.I., Laptikhovsky, V.V. and Barton, A.J., 2015. Biology and fishery of common hake (Merluccius hubbsi) and southern hake (Merluccius australis) around the Falkland/Malvinas Islands on the Patagonian Shelf of the Southwest Atlantic Ocean. *Hakes: Biology and Exploitation*, pp.154-184.

[15] Pauly D. and Zeller D. (Editors), 2015. Sea Around Us Concepts, Design and Data (seaaroundus.org).
Falkland Islands Government, 2018. Fisheries Department Fisheries Statistics, Volume 22, 2017: 100pp Stanley, FIG Fisheries Department

Hoki is one of the most abundant pelagic fish on the Patagonian shelf.[16] The stock straddles Argentine, Chilean (Pacific Coast) and Falkland waters. Hoki is not highly abundant in Falkland waters as the FICZ is at the edge of the species distribution area and its spawning grounds are outside Falkland waters. Hoki is targeted by trawlers in Falkland waters primarily during spring, summer and autumn in deep waters to the southwest of West Falkland. In winter, hoki migrate to their spawning grounds off the Chilean coast and to a lesser extent, the coast of Argentina. The observed spawning aggregations in the Southwest Atlantic are too small to sustain the observed biomass in the Southwest Atlantic suggesting that there are yet unknow spawning grounds and/or fish are migrating from the Pacific to the Atlantic oceans. Catches of hoki in Falkland Island waters have varied from 4,000 to 23,000 metric tonnes over the last decade (Figure 4). This represents anywhere from 8% to 18% of the total hoki catch in the Southwest Atlantic and 8%-20% of the Falkland Island finfish catch.

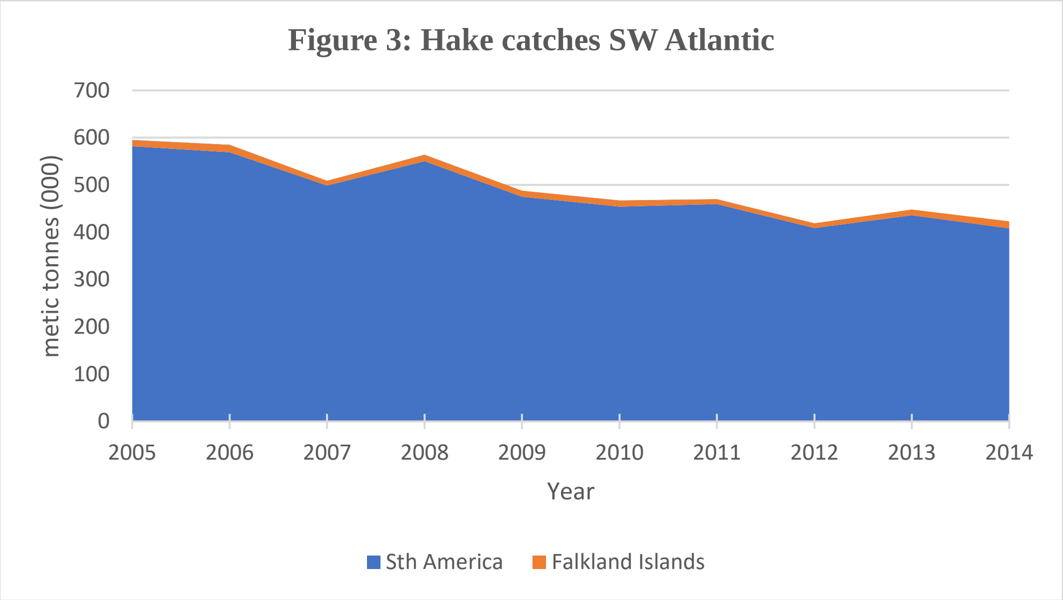

Figure 3: Hake catches SW Atlantic

Source: Pauly D. and Zeller D. (Editors), 2015. Sea Around Us Concepts, Design and Data (seaaroundus.org)

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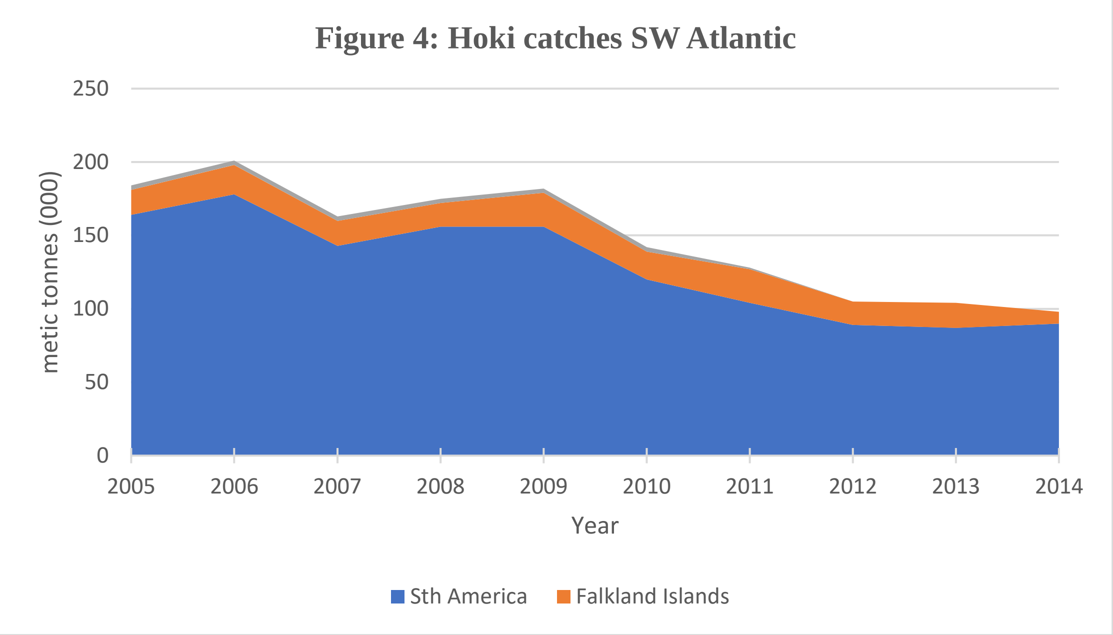
[16] Schuchert, P. C., Arkhipkin, A. I., & Koenig, A. E. 2010. Traveling around Cape Horn: Otolith chemistry reveals a mixed stock of Patagonian hoki with separate Atlantic and Pacific spawning grounds. *Fisheries Research*, *102*(1-2), 80-86



Source: Pauly D. and Zeller D. (Editors), 2015. Sea Around Us Concepts, Design and Data (seaaroundus.org)

Southern blue whiting was one of the most abundant species on the Patagonian Shelf, but the stock has declined dramatically since the 1990s with a major population crash occurring between 2004 and 2007.[17] [18] At various times of the year, southern blue whiting migrates between Chilean, Argentine and Falkland Islands waters as well as to international waters in the Scotia Sea making its management challenging.

Inshore waters to the south of West Falkland and near Chiloe Island in Chile have been identified as spawning grounds. Spawning occurs in September and October every year and the Falkland Islands have banned any fishing activity on the Falkland spawning grounds for conservation reasons since 2010. Unlike hoki and common hake, southern blue whiting is associated with colder waters to the south of the Falkland Islands. Also, southern blue whiting demonstrates limited connectivity between Southwest Atlantic and Southeast Pacific stocks which is in contrast to hoki that demonstrate high connectivity between Pacific and Atlantic stocks. Catches of southern blue whiting have varied from 2,000 metric tonnes to 22,000 metric tonnes over the last decade. Prior to 2007, the Falkland Islands could take up to 30% of the Southwest Atlantic southern blue whiting catch. The Falkland Islands share now averages 18% of the total Southwest Atlantic catch, even though Argentinian catches have fallen sharply (Figure 5). In recent years, southern blue whiting has made up less than 10% of the Falkland Island finfish catch.

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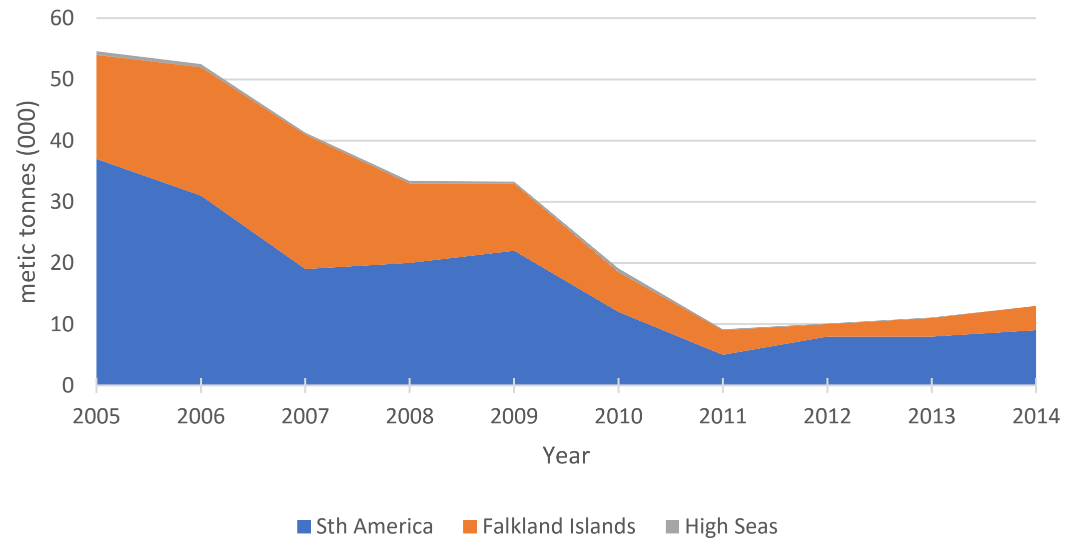
[17] McKeown, N. J., Arkhipkin, A. I., & Shaw, P. W. 2017. Regional genetic population structure and fine scale genetic cohesion in the Southern blue whiting Micromesistius australis. *Fisheries research*, *185*, 176-184

[18] Laptikhovsky, V., Arkhipkin, A. and Brickle, P. 2013 *ibid*

Figure 5: Southern blue whiting catches SW Atlantic



Source: Pauly D. and Zeller D. (Editors), 2015. Sea Around Us Concepts, Design and Data (seaaroundus.org and https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/. [19]

Illex is an oceanic squid occurring in temperate and subtropical waters between 22°S and 54°S in the SW Atlantic Ocean. The species consists of several distinct populations and cohorts, all of which have annual life cycles.[20] The main populations are winter spawners. The Southern Patagonian Stock (SPS), migrates into Falkland waters between February and June. SPS spawning grounds are found in the warm waters of the continental shelf of southern Brazil and Uruguay. The SPS constitutes one of the largest and most valuable squid fisheries in the world. Natural variability in stock abundance interacting with oceanographic conditions (in cold years, Illex may not migrate as far south as Falkland waters) means catches in Falkland Islands are highly variable, ranging from 44 tons in 2009 to 358,000 44 tonnes in 2015. Harvests were less variable in the 1990s and much more variable since 2000. In recent years about half the catch is taken in Argentinian waters, and the high seas and Falkland Islands each average 25% of the harvest (Figure 6). These proportions change from year to year. In some years the Falkland Islands and high seas have each had up to a 40% share of the catch. The fishery is dominated by foreign flagged jiggers licensed to fish in Falkland Islands waters. Trawling by domestic vessels accounts for a relatively small proportion of the overall Illex catch.

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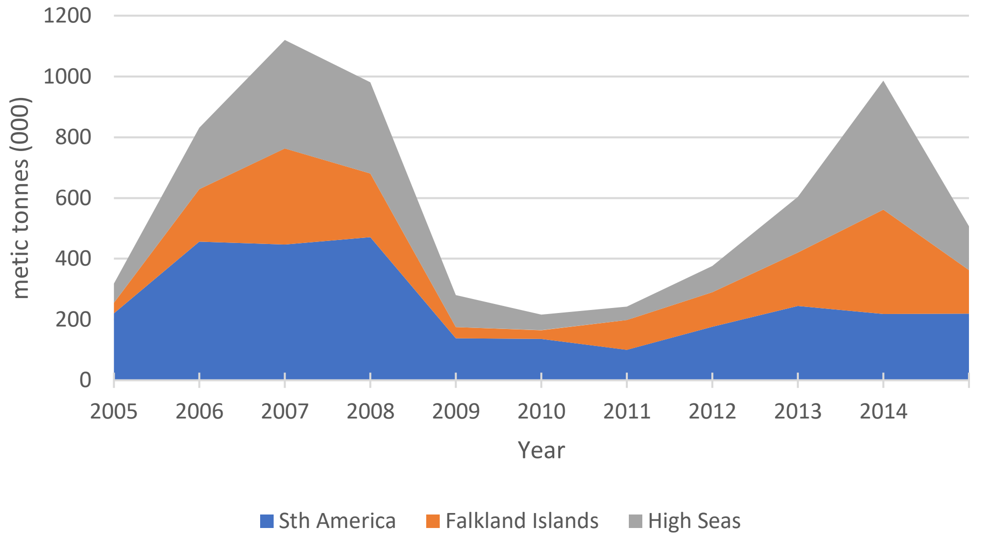
[19] Southern blue whiting catches reported by Argentinian authorities are significantly lower than those reported in the Seas Around Us database and shown in Figure 5. See https://www.agroindustria.gob.ar/sitio/areas/pesca_maritima/desembarques/. Based on discussions with the Falkland Islands Director of Fisheries we have used the reported Argentinian data for Argentinian catches.

[20] Arkhipkin, A., Barton, J., Wallace, S. and Winter, A., 2013 *Ibid*

Figure 6: Illex catches SW Atlantic



Source: Pauly D. and Zeller D. (Editors), 2015. Sea Around Us Concepts, Design and Data (seaaroundus.org)

Governance of straddling stocks and the role of game theory in understanding the benefits of international cooperation

The governance of fisheries resources that migrate between, or straddle, the waters of coastal States is always complicated and often contentious. The United Nations Law of the Sea Convention (UNCLOS) provides a basic framework for the management of shared fisheries.[21] UNCLOS addresses the fisheries management of these stocks through articles 63-64 (economic exclusive zone), and article 87 (freedom on the High Seas). UNCLOS imposes a duty upon the relevant coastal States to negotiate arrangements for transboundary stock management but it does not impose upon the States the duty to reach an agreement. If the States are unable to reach an agreement, each State should manage the segment of the transboundary stock occurring within its EEZ.

The 1995 UN Fish Stocks Agreement[22] was instituted to improve the management of straddling stocks through regional RFMOs.[23] The agreement recognizes that management of

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[21] Munro, G., Willmann, R., Van Houtte, A. (2005) The conservation and management of shared fish stocks: legal and economic aspects, FAO Fisheries Technical Paper Nº 465, Rome.

[22] Officially known as 'The United Nations Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks'.

[23] Villasante, S. and Sumaila, R., 2008. Economics of fisheries management of straddling fish stocks in the Patagonian Marine Ecosystem. In *5th World Fisheries Congress, Yokohama, Japan, October*.

shared stocks requires negotiations and agreements between the States to address issues such as access and allocation, and the use of aligned management measures. Coastal States and States with fleets fishing on the high seas should cooperate in relation to these stocks either directly or through RFMOs or through public arrangements.[24]

Within the context of UNCLOS and UN Fish Stocks agreement, the negotiations (the ‘games’) between countries over access to shared or highly migratory stocks have (in)famously been described as the “great fish war.”[25] The stakes in this fish war are high. The upsides for cooperatively governed international fisheries are sustainable and profitable fisheries, healthy marine ecosystems, food security and prosperity for fishing dependent communities. The downsides are overfished and collapsed fish stocks, decimated marine ecosystems and the squandering of the natural, financial and social capital.

States have sets of attributes (e.g., level of economic development, fisheries management capacity, access to subsidies and foreign aid, presence or absence of fisheries access agreements, domestic and distant water fishing fleet capacity, level of labour force skill, access to processing facilities and markets etc.) that both directly and indirectly impact the ability of a country to influence the game. Moreover, changes in the abundance, distribution and age structure of fish stocks due to harvest exploitation, climate variability and climate change, and the interaction of these pressure and stock responses to them, can change haves into have-nots and have-nots into haves quickly.[26] Players in the game have different objectives and thus incentives and disincentives to collaborate over the governance of international fisheries and this impacts the likelihood of stable, successful coalitions of States managing international fisheries.[27]

Gordon Munro, one of the progenitors of modern fisheries economics in general, and the use of game theory in fisheries in particular, wrote:[28]

> *it is all but impossible to analyse the economics of the management of these resources* [internationally shared fisheries], *other than through the lens of game theory. Strategic interaction between, and among, those states sharing the resources, lies at the heart of the resource management problem.*

Munro goes on to write that:

> *…there are several basic, indeed elementary, game theory concepts, which are of direct and immediate relevance to policy makers. It was also argued that these concepts are, as yet, poorly understood by the policy makers. What this requires of us is that we become effective expositors, by taking the results of our game theory analysis and expressing them in a form that can be readily understood and appreciated by the practitioners.*

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[24] United Nations (1995) United Nations Conference on straddling fish stocks and highly migratory ish stocks, A/CONF.164/37. New York.

[25] Breton, M. and M. Keoula. 2014. A great fish war model with asymmetric players. Ecological Economics 97, 209–223

[26] Walker, A. N., & Weikard, H. P. 2016. Farsightedness, Changing Stock Location and the Stability of International Fisheries Agreements. Environmental and Resource Economics, *63*, 591-611

[27] Pintassilgo, P., L.G. Kronbak and M. Lindroos. 2015. International Fisheries Agreements: A Game- theoretic Approach. Environmental and Resource Economics 62:689–709

[28] Munro, G.R. 2009. Game theory and the development of resource management policy: the case of international fisheries. Environment and Development Economics 14, 7-27

The theoretical and practical application of game theory in explaining and analysing problems of strategic interaction in fisheries in general and international fisheries specifically is well documented.[29,30]

Game-theoretic basics for straddling finfish and squid stocks in the southwest Atlantic

Fish stocks represent valuable resources straddling national EEZs as well as the high seas. These resources are common property in the sense that harvesting in one EEZ will impact stock abundance in adjacent EEZs and eventually all EEZs and the high seas where the exploited species exist. Finfish stocks are shared between the Falkland Islands, Argentina and to a lesser extent the high seas and the waters of other adjacent South American countries. Illex stocks are shared between the Falkland Islands, Argentina and the high seas.

There are three sets of players attempting to benefit from these resources:

- The Falklands;
- South American nations (predominantly Argentina and in some instances Chile and Uruguay); and
- In the case of Illex, distant water fishing fleets (DWFF).

All players want to maximize their net economic benefits from the fisheries resources. They cannot independently maximize net benefits because of the common property nature of the resource. Fish stocks on the high seas, and in the absence of bilateral agreements between countries - shared stocks, are non-excludable in the sense that one fishing operation or country cannot stop another operation from catching a share of the fish. Fish stocks are also rival resources since countries of dishing operations compete to catch shared or highly migratory stocks. This situation leads to strategic interaction between the players that can be described and analysed in game-theoretic terms.

The game-playing positions of the groups of players are different. The EEZ-nations have property rights over fisheries resource in their EEZs, which they can operate unilaterally or multi-laterally to control the utilization of the fisheries resource. The DWFF, need to cooperate with one or more EEZ-nation to exploit the resources in the coastal states EEZs or they can fish on the high seas. DWFF can be made up of multiple Flag States, and therefore even the DWFF has elements within it that may interact beyond simple competition for the high-seas resource.

The set of players is composed of the homogeneous members. The EEZ and high seas catches are of unequal size and, in the case of Illex squid, demonstrate much inter-annual variability. Since the players can communicate and form more or less binding agreements, this game may be characterized as a bargaining game. The conditions under which the game is played change over time (biomasses, distribution of stocks, prices etc.), and the bargaining game is dynamic.

Bargaining can proceed in various ways. One outcome is no agreement between the players. This would lead to very little net economic benefit in the medium to long term and overexploitation locally. The other extreme is an overall agreement by all the players, or a grand coalition, which has the potential to maximize total economic benefits from the

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[29] Bailey, M., U.R. Sumaila & M. Lindroos 2010. Application of game theory to fisheries over three decades. Fisheries Research 102, 1-8.

[30] Pintassilgo, P., L.G. Kronbak and M. Lindroos. 2015 *ibid.*

resource (and share them in a mutually beneficial way should there be such agreements). There are many other arrangements between these extremes.

A feature of all stable coalitions is that all the members believe that they are getting at least as much net benefits from their participation in the coalition as under any other option they have. In dynamic games, the members believe this at all points of time, otherwise they will exit the coalition. Not all coalitions (whether between governments or fishers) can be sustained. Coalitions are more likely to be sustained if benefits are transferable (like financial benefits) and the renegotiation of benefit distribution as conditions change is straightforward.

Villasante and Sumaila (2010) explored the economic benefits of cooperative or non-cooperative fisheries management of Illex between Argentina and the Falkland Islands.[31] The results suggest that the current situation in terms of both biomass and fishing was consistent with a non-cooperative scenario. They demonstrated that moving to a cooperative scenario would result in better economic benefits because both fleets would reduce the fishing effort and the abundance of the stock would be above target reference points. This study only looked at Illex, however, and did not introduce the complexity of Illex caught on the high seas by DWFF. Both these issues are addressed in this study.

Bioeconomic and game theory approach

We carry out an exploratory modeling study that investigates related components of the two aspects of the management of shared fisheries on the Patagonian Shelf:

1. A simple bioeconomic model for straddling stocks, with a focus on the Illex, hoki and southern blue whiting fisheries, that:
   - Estimates what the economic benefits generated in these fisheries would be if harvest levels for the shared stocks (including on the high seas) were managed to produce maximum economic yield from the fisheries;
   - Based on regional catch data, apportion gains and losses in profits between distant water fishing fleets operating on the high seas, the Argentinian fishing fleet; and vessels licensed to fish in Falkland Islands' waters.
2. Based on the bioeconomic findings, we create a simple game theory model of the straddling stock fisheries, and investigate the upside, in terms of economic and fisheries conservation benefits of increased fisheries cooperation between the United Kingdom/Falkland Islands and Argentina.

Modelling the multi-fleet fishery

In Appendix A we describe our model for the South American, Falklands and high seas fisheries, present analysis for estimating the value of cooperation between these actors,and present technical results.

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[31] Villasante, S., & Sumaila, R. 2010. Linking environmental economics, game theory and fisheries: An estimation of the economic benefits to sharing the Illex argentinus fishery in the Patagonian marine ecosystem. In *Annual Bank Conference on Development Economics (ABCDE)–Sweden. Development Challenges in a Post-Crisis World May 30th–June 2nd*

To quantify the benefit of cooperation between Argentinian and Falklands' fishing fleets we have developed a bioeconomic model. This model explicitly accounts for a number of key factors: 1) the profit of the two fleets, 2) the impact of the distant water fleet and 3) the fish stock connectivity between South American waters and Falkland Islands' waters by stock movement. With these factors in the model, we are able to define various solution concepts, specifically we compare the myopic non-cooperative, and fully-cooperative solutions.

Generic Python code for the model can be found in Appendix B.[32]

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[32] Complete Python Code is available from the South Atlantic Environmental Research Institute http://www.south-atlantic-research.org/

Results

Appendix A describes the results of the model runs graphically. The two key findings are the changes in fish or squid abundance and fleet profits in South American and Falkland Islands' waters when moving from a myopic, non-cooperative scenario to a cooperative scenario.

Table 1 shows the change in fishing effort from moving from a non-cooperative to cooperative model solution. The results are shown as a multiplier. A number greater than one is an increase in effort and a number less than one is a decrease in effort.

In all fisheries, fishing effort is lower as a consequence of cooperation. This suggest under cooperation, fleets could achieve the total allowable catch by reducing fishing effort. The reduction in Illex fishing effort is relatively modest in both South American and Falkland Islands' waters. The biggest reduction is seen in Falkland Islands fishing effort targeting hoki. This is also the fishery with the biggest differential in reductions of effort between South American and Falkland Islands' fleets. Fishing effort for southern blue whiting would be reduced by 28% and 26% respectively in South American and Falkland Islands' waters. Tables 2 and 3 reflect changes in stock abundance and profits, in part driven by the changes in fishing effort reported in Table 1.

Table 1: Fishing effort multipliers arising from cooperation

Fishery	South American waters effort multiplier	Falkland Islands waters effort multiplier
Hoki	0.94	0.36
Southern blue whiting	0.72	0.74
Illex	0.93	0.91

Table 2 shows the change in abundance from moving from a non-cooperative to cooperative model solution. The results are shown as a multiplier. A number greater than one is an increase in abundance and a number less than one is a decrease in abundance.

Table 2: Abundance multipliers arising from cooperation

Fishery	South American waters abundance multiplier	Falkland Islands waters abundance multiplier
Hoki	1.16	1.43
Southern blue whiting	1.27	1.31
Illex	1.02	1.03

In all fisheries, stock abundance increases as a consequence of cooperation. Abundance increases are highest in Falkland Islands' waters for all fisheries, though only for hoki is the increase considerably larger (43% versus 16%). Illex does not increase in abundance greatly (by 2% and 3% respectively). This is likely because of the proportion of the stock taken on the high seas by distant water fisheries fleets and the rapid growth of the species. A reduction of effort in either Falkland Islands or South American waters therefore does not have a large impact on the overall abundance of the Illex stock. Southern blue whiting increases its abundance by 27% and 31% respectively for South American and Falkland Islands' waters.

Table 3 shows the change in profits for South American and Falkland Islands' fleets from moving from a non-cooperative to cooperative model solution. The results are shown as a multiplier. A number greater than one is an increase in profit and a number less than one is a decrease in profit.

Table 3: Profit multipliers arising from cooperation

Fishery	South American waters profit multiplier	Falkland Islands waters profit multiplier
hoki	1.19	3.35
Southern blue whiting	1.06	0.15
Illex	1.00	1.48

For hoki, profits increase in South American and Falkland Islands' waters. The increase in profits accruing to the Falklands' fleet is large – some 335%. This is likely because of the higher price received by the Falklands' fleet compared to the South American fleet. Profits decrease substantially for southern blue whiting caught in Falkland Islands' waters under a cooperative solution. This is a result of the low empirical valuation of the southern blue whiting fishery, which appears to be due to price differences between the South American and Falkland Islands' fleets. Further research is needed to determine relative prices and test this result, since the reduction in relative effort (Table1) and stock abundance (Table 2) seems inconsistent with the profit results. If we give an equal empirical value to southern blue whiting in both patches, the value of cooperation is positive for both. Illex profits remain stable in South American waters and increase by some 48% in Falkland Islands' waters as a result of cooperation. This appears to be due to higher catch values for Illex caught in Falkland Islands' waters compared to South American waters.

Overall, our results show that for Illex and Hoki, the Falkland Islands have more to gain from cooperation than South American countries. In bargaining terms, the Falkland Islands could be willing to trade away some of these gains to encourage South American interests to agree to a cooperative solution. The Falkland Islands will still be better off by cooperating than not cooperating if trading away potential gains. The model results suggest an opposite case for southern blue whiting. The Falklands have much to lose from cooperation and the gains to South America are relatively small, meaning there is little incentive and limited potential for bargaining, at least in economic terms, for the Falkland Islands to cooperate over the management of southern blue whiting. The incentive in this situation is from improved stock size and wider ecological benefits of an increase in southern blue whiting abundance.

Irrespective of the distribution of fishing effort and associated profits to South American and Falkland Islands' fleets, the natural capital as measured by abundance is enhanced. Each stock is important component of the food webs of the Patagonian shelf. Greater abundance should benefit other species including seabirds and marine mammals and the wider Patagonian shelf ecosystem.

Discussion

The results show that the cooperative solution is always superior to non-cooperative solution in aggregate, leading to better overall economic and biological outcomes. Aggregate profits are higher, fishing effort is lower, stock abundance is greater, and, by inference, broader ecosystem services should increase in quality and quantity. Nevertheless, it is evident that the distribution of economic and ecological benefits depends on relative prices, costs and fisheries connectivity between South American and Falkland Islands' waters and, in the case of Illex, the high seas. Depending on the fishery (or the specification of the fishery) sometimes the Falkland Islands benefits most, sometimes South America benefits most. Sometimes, as in the case of the southern blue whiting fishery one country may actually be worse off, even though the aggregate result is superior to the non-cooperative solution.

Unequal benefits and costs lead to differing incentives and disincentives to cooperate. For two or more parties to cooperate:[33]

- They must both be better off cooperating than not cooperating and feel cooperation results in a fair and equitable outcome.
- They must be sure that the other party will cooperate and continue to cooperate – it is self-enforcing.
- They must be certain that no third party can come in and enjoy the benefits of their cooperation at their expense.

It is unclear from the preceding analysis that these conditions hold in the Southwest Atlantic. In the absence of financial mechanisms (called side payments) to compensate each territory (and its fishers), depending on the fishery they may not be better off cooperating than not cooperating and they are unlikely to feel cooperation is resulting in a fair and equitable outcome. Highly variable catches due to environmental variability and longer-term changes in stock abundance and distribution due to climate change further complicates the identification and distribution of benefits from cooperation.

Finally, in the case of Illex, the absence of an RFMO in the Southwest Atlantic means that bi-lateral cooperation could be undermined by third parties. Cooperation between South American countries and the United Kingdom/Falkland Islands would not prevent distant water fishing fleets fishing on the high seas. Having no obligation to regulate their catches, or even report their catch, these vessels will limit the economic and ecological benefits of bilateral cooperation between coastal States in the region. At the same time, the potential ecological and economic impact of these third-party free riders could provide the impetus for efforts between coastal States to establish an RFMO.

There are at least three scenarios for the future of shared Southwest Atlantic fisheries:

- The status quo: Coastal States in the Southwest Atlantic continue myopic non-cooperative fishing strategies and high seas fishing by distant water fleets increases in intensity. In this scenario, shared fish stocks continue to decline in abundance and too much aggregate effort in the fisheries leads to falling profits and economic losses for all fishery participants. The Falkland Islands do not have a sufficient share of regional harvests to place any real pressure on stock abundance in South American waters, while South American States’ fishing behaviour can impact stock abundance in Falkland Island waters. Over time, the Illex fishery shows a downward trend in stock abundance and profitability as unregulated high seas fisheries severely supresses spawning biomass in low abundance years.
- Modified status quo: The United Kingdom and Argentina cooperate on joint research cruises and agree to coordinate actions over the setting and enforcement of total allowable catches in shared fisheries. Declines in finfish stock abundance slows but rebuilding is slow, and the Falkland Islands remain dependent on significant changes in capacity and management practices in Argentine fisheries for the health of their finfish fisheries. The Illex fishery continues to show a downward trend in stock abundance and profitability due to continued unregulated high seas fishing.

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[33] Munro, G.R., 1986. The management of shared fishery resources under extended jurisdiction. *Marine Resource Economics*, *3*(4), pp.271-296.

- Enhanced international cooperation: Under this scenario Southwest Atlantic coastal States agree to, and enforce, hard catch limits and shared rebuilding strategies for overfished finfish stocks across EEZs and fleets. An RFMO consisting of coastal States and the flag States of distant water fishing fleets is established that begins to put in place conservation management measures that further scaffold coastal State rebuilding strategies for finfish and begin to regulate high seas fishing effort for Illex. Regional fisheries management meets or exceeds the performance of other major global fishing regions.

Even the creation of an RFMO would still need many years for agreement to reached between cooperating states and for this cooperation to bring about ecological and economic improvements. A more realistic trajectory is from the status quo to a modified status quo that builds on current efforts to re-establish the Southwest Atlantic fisheries Commission.

Whether or not substantive economic and biological benefits are forthcoming depends greatly on the political will and institutional capacity of Commission members to bring about change in their respective fisheries. Even with regional stock rebuilding and recovery of the fisheries, the economic and ecological benefits to the Falkland Islands are uncertain because of the Falkland Islands' smaller fishing effort targeting shared stocks in Falkland Islands' waters. In the absence of an RFMO, Argentina and the United Kingdom still have a common interest in reducing high seas fishing effort targeting Illex and could work with European and other markets to regulate and restrict the importation of unreported and unregulated Illex catch taken on the high seas.

Conclusion

The Southwest Atlantic is home to some of the most productive fisheries in the world. This rich natural capital underpins a dynamic, thriving economy and society in the Falkland Islands, supports coastal communities in South America and contributes to vibrant seafood markets in Asia and Europe. Yet the future of these fisheries is far from assured and the region lags behind all but the worst regional performers in terms of the percentage of fish stocks managed at sustainable levels.

Bioeconomic and game theoretic studies, including this one, consistently show that the biological and economic benefits of cooperation are greater than the benefits of non-cooperation. Yet bilateral and multilateral cooperation between States over shared fisheries resources is hard to achieve. Coastal and flag States tend to pursue myopic non-cooperative strategies. When cooperation does occur, it often fails to realize the full suite of improvements to natural capital possible. This is because the real world is more complex than can be represented in an abstract model, no matter how sophisticated.

This is particularly so in the Southwest Atlantic. The ongoing sovereignty dispute between the United Kingdom and Argentina over the Falkland Islands impacts bilateral cooperation over shared fisheries and overshadows potential multi-lateral discussions to create an RFMO for the Southwest Atlantic. Both the Falkland Islands and Argentina are facing the increasing unreported and unregulated harvest of Illex on the high seas further pressuring Illex stocks in last few years. Our analysis suggests that although cooperation increases aggregate economic and ecological benefits, the distribution of these benefits between the different actors is far from even. The economics of each fleet and the connectivity between stocks drives the disparities and hence incentives and disincentives to cooperate.

Adding to the complexity and uncertainty of management is the impact of climate driven changes on Southwest Atlantic fisheries. Though the impact is unknown, there have been abrupt changes in catches observed during the last decade. Climate-driven changes in stock range and distribution may exacerbate ecological, economic, food and conflict-related insecurity. These conflicts will be amplified by the failure to coordinate the management of regional stocks that straddle or migrate between the waters of different countries and between exclusive economic zones and the high seas.

Both coastal and flag States in the Southwest Atlantic have good reason to cooperate to address unsustainable levels of fishing effort, illegal, unregulated and unreported fishing, and the consequences of climate change. Regional geopolitics, however, mean that enhanced bilateral and multilateral cooperation is difficult to achieve. Even the creation of an RFMO in the medium term would need many years for agreement to reached between cooperating states and for this cooperation to bring about change. In the short to medium term two strategies seem the most likely to have the most success:

- Coordinated exchange of fisheries data, joint research cruises, joint scientific analysis, and fisheries advice to respective governments through the South Atlantic Fisheries Commission; and
- Coordinated action by Argentinian and Falkland Islands Illex-based exporters aimed at eliminating the importation of unregulated and unreported high seas Illex catches by European and other key markets.

Appendix A: Bioeconomic Model and Results

The model is a spatially explicit two-patch bioeconomic model, which describes the change in biomass density of a given fished species in South American waters and Falkland Island waters. These are the two patches in the model which are simply labelled as patch 1 and 2. The model advances in discrete yearly increments. Migration of adult stock is allowed between the patches and is determined by two migration parameters: the magnitude and asymmetry of migration. These parameters specify the fraction of a stock in one patch that moves to the other in a given year. The fish population grows logistically, and fishing mortality is modelled linearly. With these specifications, the rate of change in biomass density of a given fish species in patch 1 is:

$$\Delta R_1 = rR_1(1 - \frac{R_1}{K}) - \epsilon_1 R_1 - \alpha R_1 + (1-m)\beta R_2,$$

and similarly, for patch 2:

$$\Delta R_2 = rR_2(1 - \frac{R_2}{K}) - \epsilon_2 R_2 - \beta R_2 + (1-m)\alpha R_1,$$

where r is population growth rate of the fish species, K is the carrying capacity, ε_i is the fishing effort of each fleet in patch 1 and 2, α is the fraction of the stock in patch 1 that moves to patch 2 and β is the fraction of stock in patch 2 that moves to patch 1. m is the impact of the distant water fleet on the migrating stocks.
With these equations it is natural to then specify the profits of the fishing fleet in patch 1:

$$\pi_1 = p\epsilon_1 R_1 - c\epsilon_1^2,$$

and in patch 2:

$$\pi_2 = p\epsilon_2 R_2 - c\epsilon_2^2,$$

where p is the price of the fish and c is the cost per unit fishing effort, which is modelled quadratically.

Simulation Experiments

These dynamic equations have solution concepts that can be identified analytically, but here for ease of use and flexibility, we perform numerical simulations (using a simple forward Euler scheme) to calculate the dynamic equilibria for these equations, which we use in parameter sweeps to identify the key solution concepts. In particular, we focus on differences in non-cooperative and cooperative efforts on resulting profits and fish stocks:

1) The myopic non-cooperative solution is the effort level chosen by a given fishing fleet that maximizes their profits, without taking in consideration the action of the other fleet.
2) The fully cooperative solution is the effort level chosen by a given fishing fleet that maximizes the combined profits from each fleet.

These solutions are defined as a function of the population growth rate r, the impact of the distant-water fleet m, and the impact of various magnitudes and asymmetries in patch connectivity. For each choice of these parameters, the full range of fishing effort in patch 1 and 2 is explored, and from these results the non-cooperative and fully cooperative solutions are identified and compared. Note, for all simulations the carrying capacity is set to unity, so results are posed in relative terms, and do not have units comparable to those obtained from empirical data on the costs and profits of fishing fleets in the Falklands/Argentinian system. The utility of this model is in the comparison of qualitative results, specifically in being able to identify for certain conditions when cooperation will benefit both fishing fleets or when cooperation will benefit one fleet more than another.

Using Empirical data to model the hoki, Illex and southern blue whiting fisheries

The model described above is necessarily abstract to compare and contrast outcomes from different behavioural choices (i.e. cooperative or non-cooperative effort levels). Even so, certain choices of parameters can allow us to explore areas of the parameter space that reflect key biological and social characteristics of the hoki, Illex and southern blue whiting fisheries. Specifically, the following parameter choices were made:

Hoki: the growth rate of the fish (r) = 1.5; the ratio of the price of fish to the cost of fishing = 4; harvest impact of the distant water fleet (m) = 0.01; the fraction of the South American population that moves to the Falkland Islands patch (α) = 0.9; the fraction of the Falkland Islands population that moves to the South American patch (ß)) = 0.1.

Illex: the growth rate of the fish (r) = 3; the ratio of the price of fish to the cost of fishing = 4; harvest impact of the distant water fleet (m) = 0.3; the fraction of the South American population that moves to the Falkland Islands patch (α) = 0.7; the fraction of the Falkland Islands population that moves to the South American patch (ß)) = 0.3

Southern blue whiting: the growth rate of the fish (r) = 1. 1; the ratio of the price of fish to the cost of fishing = 4; harvest impact of the distant water fleet (m) = 0.01; the fraction of the South American population that moves to the Falkland Islands patch (α) = 0.1; the fraction of the Falkland Islands population that moves to the South American patch (ß) = 0.9

In addition to these parameterizations, we additionally use economic information on the value of these fisheries. Specifically, we assume that the equilibrium profits produced from the model under myopic non-cooperative behaviour is equivalent to the median total fishery value (USD).[34] This operation is done to essentially scale the (normalized) results of the model to those reflecting real-world value. Importantly, this operation is done before the cooperative solution is identified, and thus differences in empirical fishery values from patch 1 (South American waters) and patch 2 (Falkland Islands waters) will impact the cooperative effort levels. The median total fishery values for the hoki, Illex and southern blue whiting South American and Falkland Islands fisheries respectively were (in millions of USD): 153 and 29, 235 and 176, and 22 and 4.75.

Model runs

The model was solved using standard forward in time numerical integration methods. The model is deterministic and does not address variability or uncertainty in model structure or parameters, so only one run is required per parameter set. This choice was made so that the model could be used to focus on the game theoretic solutions to cooperative fishing. The parameter sets that were swept through included a 50x50 grid, relating to the effort combinations of the different fleets. For three species, the parameter sweeps then led to 7500 model runs.

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[34] Sea Around Us: http://www.seaaroundus.org/ This database was used to evaluate Illex ex-vessel landings in terms of volume (MT) and value (USD) across the main capture regions: the Argentine EEZ, Falkland Islands EEZ, and the high seas. This database, compiled and updated by the University of British Columbia is the only one freely available providing comparable time series data across these regions using a consistent method.

Model Results

For a given choice of the population growth rate *r*, the impact of the distant-water fleet *m*, and the magnitude and asymmetry of connectivity, the fishing effort in patch 1 and patch 2 are swept through, with equilibrium abundances and profits calculated. For example, see Figure A1 for results for the three fisheries in patch 1 (South American waters) and 2. Myopic non-cooperative efforts are identified as those that maximize an individual fleets profits, ignoring what the other fleet does. This naturally occurs when fleet *i* assumes that fleet *j* does not harvest: at this point there is an increase in fishing profits to a maxima (Figure A1 dark red regions peaks in both patch 1 and 2, identified by the green triangle) past which profits start to diminish. This is analogous to fishing effort that leads to maximum sustainable rent.

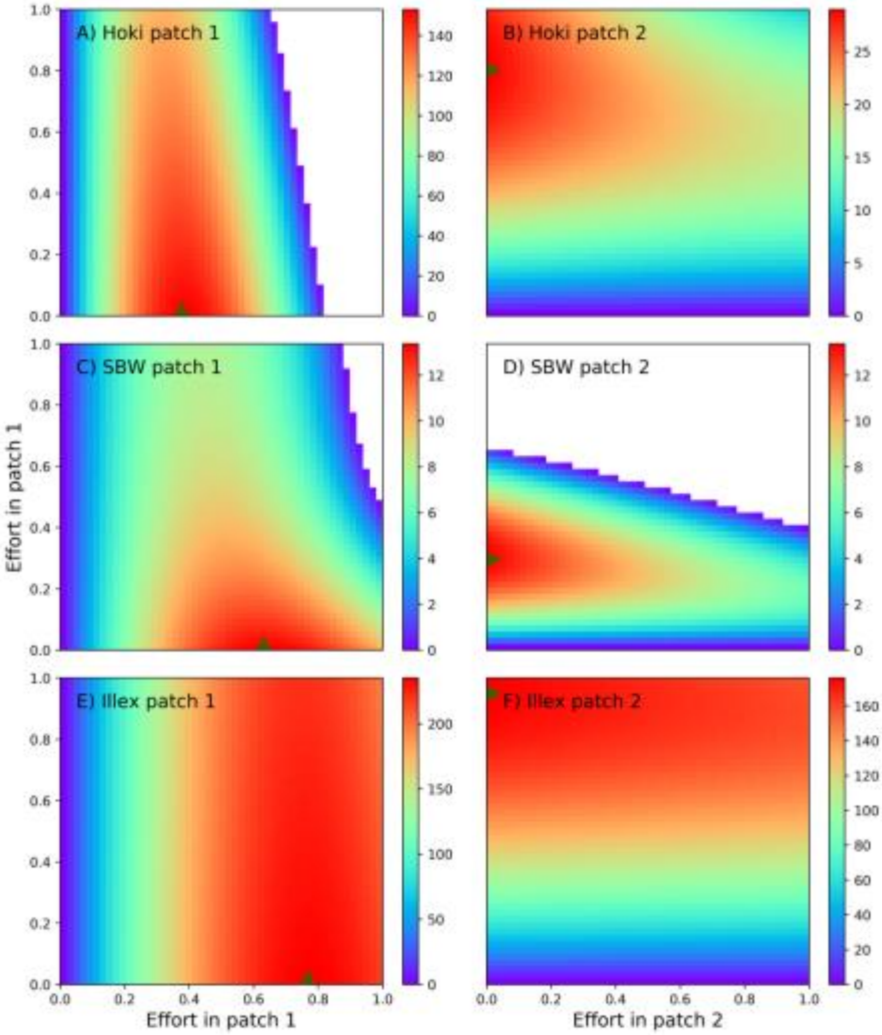

Figure A1. Profits in patch 1 (left) and patch 2(right) as a function of fishing effort in patch 1 (x-axes) and patch 2 (y-axes). Results are shown for one choice of the set of key parameters: the population growth rate *r*, the magnitude and asymmetry of connectivity and the impact of the distant-water fleet *m*. The green arrows identify the myopic non-cooperative solution: the effort of a given fishing fleet that maximizes its profits, without taking in consideration the action of the other fleet.

To find the fully cooperative effort levels we explore the total profit space (Figure A2: this is the sum of profits from both patches, the left and right panels in Fig. A1). The total profit space is characterized by a peak corresponding to optimal cooperative effort levels (Figure A2, teal arrows on the y- and x-axes). Note, these cooperative effort levels are less than those of the myopic non-cooperative effort levels. Further, the cooperative total profit is different from the non-cooperative total profits (Figure A2 compare teal dot and green star markers). The increase in profits experienced by the different fishing fleets under a cooperative arrangement is shown at the top of each panel in Fig. A2: in every case but one profits increase. The case where profits decrease is southern blue whiting patch 2. This is a result of the low empirical valuation of the southern blue whiting fishery, which likely results from price differences between the South American and Falkland Islands patches. Given an equal empirical value assignment to southern blue whiting in both patches, the total value of cooperation is positive.

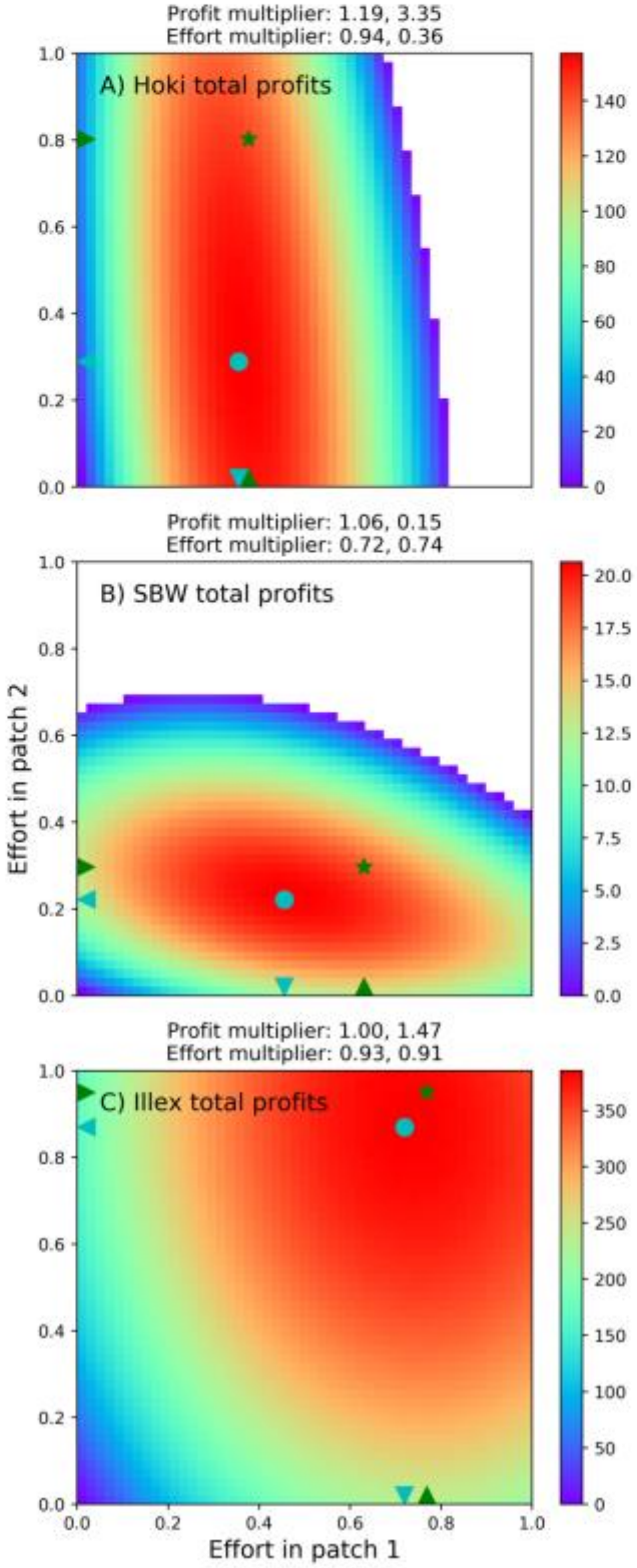

Figure A2. The combined profits from both fishing fleets (i.e. the sum of the left and right panels in figure A1). Here the cooperative optimal is evident as the teal dot, and from here the cooperative efforts of each fleet can be identified by the teal arrows. Note that they are less than the myopic non-cooperative solutions (green arrows) which lead to a sub-optimal solution (green star).

In addition to these differences in profits, as a function of non-cooperative and cooperative effort levels, there are differences in the stock abundances in each patch (Figure A3). Changes in equilibrium resource abundances between the non-cooperative and cooperative arrangements are identified in Patch 1 and 2 (left and right panels respectively) by the white star and dot respectively. In every case, because cooperative effort levels are lower than the non-cooperative levels, the equilibrium stock levels are higher.

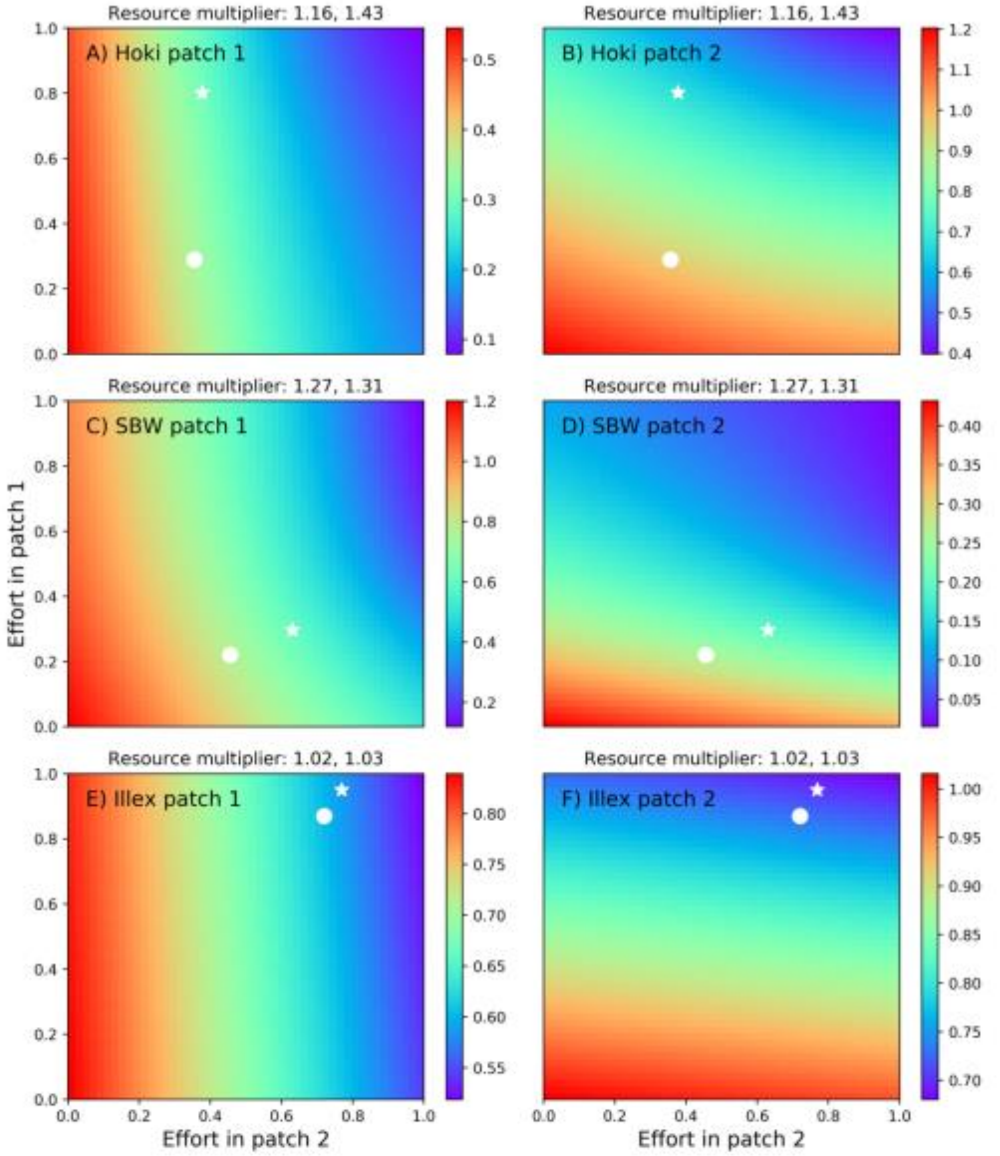

Figure A3. Abundance of each fish stock in patch 1 (left) and patch 2 (right). The cooperative (white dot) and non-cooperative (white star) solutions are identified, and it is evident that the cooperative solution leads to higher abundance.

Appendix B: Python code for bioeconomic model and game theory extensions

```
plt.show()
from scipy.optimize import fsolve
from scipy.optimize import root
import numpy as np
import matplotlib.pylab as plt

###### Parameters
alpha = 0.9 # fraction of patch 1 that moves to patch 2
beta = 0.1 # fraction of patch 2 that moves to patch 1
p = 4 # price of fish (falklandz)
c = 1 # cost of fishing (falklandz)
r = 1.5 # growth rate of fish
m = 0.01; # impact of distant fleet
K = 1 # carrying capacity
Tmax = 1000
dt = 0.1

### Sweep through effort
EF1 = np.linspace(0,1,50)
EF2 = np.linspace(0,1,50)
EQ_prf1 = np.zeros((len(EF1),len(EF2)))
EQ_prf2 = np.zeros((len(EF1),len(EF2)))
EQ_R1   = np.zeros((len(EF1),len(EF2)))
EQ_R2   = np.zeros((len(EF1),len(EF2)))

for i in np.arange(0,len(EF1)):
    for j in np.arange(0,len(EF2)):
        print(i,j)

        ### Savers
        R1 = np.zeros(Tmax)
        R2 = np.zeros(Tmax)
        R1[0] = 1
        R2[0] = 1
        PRF1 = np.zeros(Tmax-1)
        PRF2 = np.zeros(Tmax-1)

        ### Dynamics
        for t in np.arange(0,Tmax-1):
            dR1 = ((R1[t]*r) * (1-R1[t]/K)) - (EF1[i]*R1[t]) - \
                    (alpha*R1[t]) + ((1-m)*beta*R2[t])
            dR2 = ((R2[t]*r) * (1-R2[t]/K)) - (EF2[j]*R2[t]) - \
                    (beta*R2[t]) + ((1-m)*alpha*R1[t])

            PI1 = (p*EF1[i]*R1[t]) - (c*EF1[i]**2)
            PI2 = (p*EF2[j]*R2[t]) - (c*EF2[j]**2)
```

```
            R1[t+1] = R1[t] + (dR1 * dt)
            R2[t+1] = R2[t] + (dR2 * dt)
            PRF1[t] = PI1 * dt
            PRF2[t] = PI2 * dt

        EQ_prf1[i,j] = PRF1[-1]
        EQ_prf2[i,j] = PRF2[-1]
        EQ_R1[i,j]   = R1[-1]
        EQ_R2[i,j]   = R2[-1]


######### Find non-cooperative optimal efforts and payoff
from scipy.interpolate import interp1d
from scipy.optimize import fmin

#### Opt effort in patch 1
x = EF1
y = EQ_prf1[:,0]
i = np.where(y == y.max())[0]
f = interp1d(x, y, kind='cubic', bounds_error=False)
f2 = interp1d(x, -y, kind='cubic',bounds_error=False)
xmax1 = fmin(f2, x[i])
ymax1 = f(xmax1)
plt.figure()
plt.plot(x,y)
plt.plot(xmax1,ymax1,'ro')
plt.xlabel('Effort')
plt.ylabel('Profit')
plt.title('Optimal effort patch 1')
plt.savefig("./Figs/PNG/Fig_noncoopeff1.png",dpi=400)

#EF1_noncoop = xmax1[0]
#plt.figure()
#plt.pcolormesh(ef1,ef2,EQ_prf1,cmap="nipy_spectral"), plt.colorbar()
#plt.plot(EF1_noncoop,0,'^g',ms=10)

#### Opt effort in patch 2
x = EF2
y = EQ_prf2[0,:]
i = np.where(y == y.max())[0]
f = interp1d(x, y, kind='cubic', bounds_error=False)
f2 = interp1d(x, -y, kind='cubic',bounds_error=False)
xmax2 = fmin(f2, x[i])
ymax2 = f(xmax2)
plt.figure()
plt.plot(x,y)
plt.plot(xmax2,ymax2,'ro')
plt.xlabel('Effort')
plt.ylabel('Profit')
```

```
plt.title('Optimal effort patch 2')
plt.savefig("./Figs/PNG/Fig_noncoopeff2.png",dpi=400)

EF1_noncoop = xmax1[0]
EF2_noncoop = xmax2[0]

### Find NASH efforts
#i = np.where(EQ_prf1 == EQ_prf1.max())[0][0]
#j = np.where(EQ_prf2[i,:] == EQ_prf2[i,:].max())[0][0]

### Simulate to get payoff
R1 = np.zeros(Tmax)
R2 = np.zeros(Tmax)
R1[0] = 1
R2[0] = 1
PRF1 = np.zeros(Tmax-1)
PRF2 = np.zeros(Tmax-1)

### Dynamics
for t in np.arange(0,Tmax-1):
    dR1 = ((R1[t]*r) * (1-R1[t]/K)) - (EF1_noncoop*R1[t]) - \
          (alpha*R1[t]) + ((1-m)*beta*R2[t])
    dR2 = ((R2[t]*r) * (1-R2[t]/K)) - (EF2_noncoop*R2[t]) - \
          (beta*R2[t]) + ((1-m)*alpha*R1[t])

    PI1 = (p*EF1_noncoop*R1[t]) - (c*EF1_noncoop**2)
    PI2 = (p*EF2_noncoop*R2[t]) - (c*EF2_noncoop**2)

    R1[t+1] = R1[t] + (dR1 * dt)
    R2[t+1] = R2[t] + (dR2 * dt)
    PRF1[t] = PI1 * dt
    PRF2[t] = PI2 * dt

### Non-cooperative payoff
Payoff_noncoop1 = PRF1[-1]
Payoff_noncoop2 = PRF1[-1]
eq_noncoop_R1 = R1[-1]
eq_noncoop_R2 = R2[-1]

### Timeseries plot
plt.figure()
plt.plot(PRF1)
plt.plot(PRF2)
plt.xlabel('Time')
plt.ylabel('Profit (2 patches)')
plt.title('Max profit time series')
plt.savefig("./Figs/PNG/Fig_coopsim.png",dpi=400)

######### Find Cooperative optimal efforts and payoff
from scipy.interpolate import interp2d
```

```
# Normalize results to get real-world ball park
EX = 153 # ave total catch value (assume to be non-cooperative value)
arr = np.abs(EF1 - EF1_noncoop)
i = np.where(arr == arr.min())[0]
EQ_prf1 = (EQ_prf1 / EQ_prf1[i,0]) * EX

EX = 29 # ave total catch value (assume to be non-cooperative value)
arr = np.abs(EF2 - EF2_noncoop)
i = np.where(arr == arr.min())[0]
EQ_prf2 = (EQ_prf2 / EQ_prf2[0,i]) * EX

### Total profit
TOT = EQ_prf1+EQ_prf2

#### Cooperative effort in patch 1+2
x = np.linspace(0,1,1000)
y = np.linspace(0,1,1000)
f = interp2d(EF1, EF2, TOT, kind='cubic', bounds_error=False)
z = f(x,y)
max_z = np.max(z)
i,j = np.where(z==max_z)
EF1_coop = x[i][0]
EF2_coop = y[j][0]

#from scipy.interpolate import griddata
#f2 = interp2d(EF1, EF2, -TOT, kind='cubic')
#xmax1 = fmin(f2, [0.5,0.5])
#ymax1 = f(xmax1)

### Simulate to get payoff
R1 = np.zeros(Tmax)
R2 = np.zeros(Tmax)
R1[0] = 1
R2[0] = 1
PRF1 = np.zeros(Tmax-1)
PRF2 = np.zeros(Tmax-1)

### Dynamics
for t in np.arange(0,Tmax-1):
    dR1 = ((R1[t]*r) * (1-R1[t]/K)) - (EF1_coop*R1[t]) - \
            (alpha*R1[t]) + ((1-m)*    beta*R2[t])
    dR2 = ((R2[t]*r) * (1-R2[t]/K)) - (EF2_coop*R2[t]) - \
            (beta*R2[t]) + ((1-m)*     alpha*R1[t])

    PI1 = (p*EF1_coop*R1[t]) - (c*EF1_coop**2)
    PI2 = (p*EF2_coop*R2[t]) - (c*EF2_coop**2)

    R1[t+1] = R1[t] + (dR1 * dt)
    R2[t+1] = R2[t] + (dR2 * dt)
    PRF1[t] = PI1 * dt
```

```
    PRF2[t] = PI2 * dt

### Non-cooperative payoff
Payoff_coop1 = PRF1[-1]
Payoff_coop2 = PRF2[-1]
eq_coop_R1 = R1[-1]
eq_coop_R2 = R2[-1]

####### Benefits of cooperation
B_coop1 = Payoff_coop1 / Payoff_noncoop1
B_coop2 = Payoff_coop2 / Payoff_noncoop2
R_coop1 = eq_coop_R1 / eq_noncoop_R1
R_coop2 = eq_coop_R2 / eq_noncoop_R2

####### Plot
ef2,ef1 = np.meshgrid(EF2,EF1)

plt.figure()
plt.pcolormesh(ef1,ef2,EQ_prf1,cmap="nipy_spectral"), plt.colorbar()
plt.plot(EF1_noncoop,0,'^g',ms=20)
plt.title('Profits patch 1')
plt.xlabel('Effort patch 1')
plt.ylabel('Effort patch 2')
plt.savefig("./Figs/PNG/Fig_hoki_prf1.png",dpi=400)

plt.figure()
plt.pcolormesh(ef1,ef2,EQ_prf2,cmap="nipy_spectral"), plt.colorbar()
plt.plot(0,EF2_noncoop,'>g',ms=20)
plt.title('Profits patch 2')
plt.xlabel('Effort patch 1')
plt.ylabel('Effort patch 2')
plt.savefig("./Figs/PNG/Fig_hoki_prf2.png",dpi=400)

plt.figure()
plt.pcolormesh(ef1,ef2,TOT,cmap="nipy_spectral"), plt.colorbar()
plt.plot(EF1_noncoop,EF2_noncoop,'*g',ms=10)
plt.plot(EF1_coop,EF2_coop,'oc',ms=10)
plt.plot(EF1_noncoop,0,'^g',ms=20)
plt.plot(0,EF2_noncoop,'>g',ms=20)
plt.plot(EF1_coop,0.02,'vc',ms=10)
plt.plot(0.02,EF2_coop,'<c',ms=10)
plt.title('Profit multiplier: ' + np.str(B_coop1)[0:4] + ', ' + np.str(B_coop2)[0:4])
plt.xlabel('Effort patch 1')
plt.ylabel('Effort patch 2')
plt.savefig("./Figs/PNG/Fig_hoki_tot.png",dpi=400)

plt.figure()
plt.pcolormesh(ef1,ef2,EQ_R1,cmap="jet"), plt.colorbar()
plt.plot(EF1_noncoop,EF2_noncoop,'*w',ms=10)
plt.plot(EF1_coop,EF2_coop,'ow',ms=10)
```

```
plt.title('Abundance patch 2')
plt.xlabel('Effort patch 1')
plt.ylabel('Effort patch 2')
plt.title('Resource multiplier: ' + np.str(R_coop1)[0:4] + ', ' + np.str(R_coop2)[0:4])
plt.savefig("./Figs/PNG/Fig_hoki_R1.png",dpi=400)

plt.figure()
plt.pcolormesh(ef1,ef2,EQ_R2,cmap="jet"), plt.colorbar()
plt.plot(EF1_noncoop,EF2_noncoop,'*w',ms=10)
plt.plot(EF1_coop,EF2_coop,'ow',ms=10)
plt.title('Abundance patch 2')
plt.xlabel('Effort patch 1')
plt.ylabel('Effort patch 2')
plt.title('Resource multiplier: ' + np.str(R_coop1)[0:4] + ', ' + np.str(R_coop2)[0:4])
plt.savefig("./Figs/PNG/Fig_hoki_R2.png",dpi=400)

plt.show()
```