An agent-based model of IUU fishing in a two-state system with information sharing

A Cebr report for The Pew Charitable Trusts

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Executive Summary

The purpose of this research is to examine the impacts of information sharing between neighbouring coastal states on the prevalence of illegal, unregulated, or unreported (IUU) fishing activities and the overall health of fisheries. Specifically, the studies seek to determine whether co-operation between countries via the sharing of detection information – a key element of the Port State Measures Agreement – can deter and reduce IUU fishing while also boosting the level of biomass in the fisheries. The analysis is carried out through the development of an agent-based model (ABM) of IUU fishing comprising two representative coastal states that share a sea border and have independent enforcement frameworks. A series of fishing vessels conduct fishing operations within this environment, with each vessel having the option of conducting either legal or IUU activities. Each of the two countries' jurisdictions contain part of the same shared fishery resource, meaning that actions taken by one country will impact upon its neighbour.

The incentive for fishing vessels to operate illegally is a lower cost curve. The underlying assumption behind this is that fishing vessels conducting IUU activities will often face lower costs than those operating legally, for instance through the use of prohibited forms of fishing equipment or methods. Meanwhile, the disincentive is the risk of being detected and fined at a rate proportional to the profits obtained during the fishing trip. Each country has a single port and a pre-determined number of enforcement agents that patrol its waters on the look-out for fishing vessels that are engaged in IUU fishing. The ABM does not seek to specify the technologies deployed to detect IUU activity. Therefore, a country's enforcement agents can be taken to represent a variety of modes of inspection, ranging from physical patrol boats to remote sensing. When an enforcement agent detects an instance of an IUU activity, they can inform their home port about which fishing vessel was conducting the illicit act, allowing for the appropriate penalty to be imposed when that fishing vessel returns to port to land its catch.

Enforcement agents share their detection information with the port authority in their country. Moreover, depending on the level of information sharing in the model, enforcement agents may also share their detection information directly with the port authorities in the neighbouring coastal state, which increases the probability of detecting fishing vessels that conduct IUU activities in one jurisdiction before crossing the sea border to land their catch in the second country. A range of scenarios are modelled in order to uncover the degree to which information sharing can affect levels of biomass, the frequency of IUU activities, as well as the fishery yield. The scenarios can be largely be grouped into two categories:

- Homogeneous enforcement regimes, where both countries have a relatively high level of enforcement, as measured by the number and effectiveness of enforcement agents.

- Heterogeneous enforcement regimes, where one country (country B) has a relatively high level of enforcement and the other country (country A) has a lower level of enforcement, with half the number of enforcement agents patrolling its waters.

For the case of both homogeneous and heterogeneous enforcement regimes, five scenarios were modelled:

1. No information sharing i.e. enforcement agents only share information with their home port and not with the neighbouring port;

2. Partial information sharing from country B to country A, where enforcement agents in country B share half of their detection information with the port in country A;
3. Full information sharing from country B to country A, where enforcement agents in country B share all of their detection information with the port in country A;
4. Partial information sharing from both countries, where the enforcement agents of both countries share half of their detection information with the port in the neighbouring country;
5. Full information sharing from both countries, where the enforcement agents of both countries share all of their detection information with the port in the neighbouring countries.

The key findings from the analysis are:

- Information sharing boosts levels of biomass in both countries, even when only one country's enforcement agents are sharing information. This is because, the coastal states are in essence managing a shared fishery resource, meaning that an increase in the level of biomass in one country's waters will eventually filter through into the neighbouring country's waters through the movements of the fish population. With that being said, when there is a one-way flow of information, the greatest beneficiary is the country that is sharing the information, since this directly deters IUU fishing activities by increasing the risks of detection for fishing vessels. This shows that while domestic policies and practises are critical in countering IUU fishing, frameworks that promote information and resource sharing between countries – such as the Pacific Maritime Security Program in the South West Pacific – also represent a powerful and cost-effective way of supporting international fisheries. These results highlight that the sharing of information is not a case of the prisoner's dilemma, in which it is in neither party's individual self-interest to co-operate despite the mutual benefits that can be unlocked if they do. By contrast, the principal beneficiary of information sharing is the party sharing the information, meaning that equilibrium outcomes with high levels of co-operation are feasible – and indeed likely – if countries are equipped with the technological, operational and legal means to do so.

- In the absence of information sharing, fishing vessels are able to conduct IUU activities in one jurisdiction before landing their catch in the port in the neighbouring country, without any risk of detection. Information sharing allows ports to impose penalties on fishing vessels that conducted IUU activities in another jurisdiction. As a result, the probability of being sanctioned rises with levels of information sharing, which consequently deters fishing vessels from carrying out IUU acts. This is observed consistently in the modelling simulations. In the case of homogenous enforcement regimes, the share of fish caught illegally each period tends to exceed 40% when there is no information sharing taking place. IUU activity is largely eradicated when there is full information sharing by both countries, with typically less than 1% of fish caught illegally in any given period by the end of the modelling simulations. In the case of heterogeneous enforcement regimes, the share of fish caught illegally hovers around 9% in the low enforcement country when there is full and bilateral information sharing, compared to 41% in the case of no information sharing. The higher prevalence of IUU operations are observed because the laxer regulatory environment means that IUU activities remain attractive to a minority of fishing vessels in the fishing fleet even when there is full information sharing.

- Information sharing also leads to a structural shift over time in the characteristics and preferences of the fishing fleet. This is because, higher levels of information sharing mean that fishing vessels that carry out IUU activities are more likely to be detected, which in turn lowers their profitability as a result of the corresponding fines. This makes fishing vessels with a tendency to operate illegally (i.e. those with a higher IUU-propensity coefficient) more likely to exit the market than they would otherwise have been. Over time, this leads to a fall in the average IUU-propensity across the fishing fleet, which also lowers the frequency of IUU actions. When there is full information sharing between both countries, the average IUU-propensity settles at around 0.26 in the long run. This compares to a value of around 0.38 in the case of no information sharing.

- There is a clear and positive relationship between information sharing and the health of fish populations. This comes about due to the reduced frequency of IUU actions that take place in scenarios with more information sharing. Due to the nature of the cost curve associated with IUU fishing, fishing vessels that operate illegally tend to extract larger quantities of fish than vessels operating legally. This means that a fall in the number of IUU acts will generally bring about an increase in the level of biomass. The combination of higher levels of biomass and a lower share of fish that are caught illegally mean that the legal fishery yield rises significantly in scenarios with a greater degree of information sharing between countries. However, the total fishery yield is lower in scenarios with more information sharing, since average catch sizes are generally higher when there is a high prevalence of IUU activity.

- In the case of homogeneous enforcement structures, the long-run level of biomass averages in both countries is 186,122 in the case of no information sharing between the countries. This figure rises to 214,010 when country B’s enforcement agents share half of their detection information with country A, and 242,479 when country B’s enforcement agents share all of their information with the port in country A. However, the most sizeable gains are realised when there is a two-way flow of information. Indeed, the long-run level of biomass across both countries reaches 266,068 when both countries’ enforcement agents share half of their detection information with the neighbouring port. This figure rises to 288,433 in the case of full information sharing by both countries – 55% higher than the level observed when there is no information sharing.

- The results listed above show the significant effect that information sharing can have in raising levels of biomass and discouraging IUU fishing. However, this is under the assumption that ports are able to receive, store, analyse and apply the incoming data that they receive. In many instances this is not the case, since technological, logistical or institutional barriers constrain ports’ ability to impose fines on fishing vessels, even if they have been sent information that suggests they have been conducting IUU activities. To capture this, the impact of capacity constraints at the port in the low enforcement country is considered. The results show that capacity constraints do indeed stymie the impact of information sharing. When the low enforcement country has minor capacity constraints (where for every four incoming vessels that the port has been told have operated illegally, only three will have the appropriate penalty imposed), the long-run level of biomass in the context of full information sharing falls by 9%. There is a further 9% decline in the case of major capacity constraints (where for every four incoming vessels that the port has been told have conducted IUU activities, only two are sanctioned). When there are minor capacity constraints in one country but both countries otherwise have a relatively high level of enforcement with full information sharing, there is only a muted impact on outcomes in the fishery, since enforcement structures are strong enough to deter the vast majority of IUU activities even when there are some capacity constraints. When these capacity constraints become more significant however, there is a notable impact on the levels of biomass and the prevalence of IUU activity.

- Another important consideration for countries is the revenue generated from the imposition of fines on fishing vessels that are found to have conducted IUU operations. These revenues can provide an important source of funds that can directed towards improving enforcement capabilities. It is assumed that all of the fine revenues are allocated to the country in which the IUU catch is landed. In scenarios with no information sharing, revenue from fines is very low in both countries since neither port authority can sanction fishing vessels that have conducted IUU activities but crossed the border to land their catch. In the case of homogeneous enforcement structures, revenue from fines is maximised when there is partial information sharing by both countries. Under these conditions, there is still some degree of IUU activity taking place, but port authorities are now able to detect and sanction a greater proportion of fishing vessels that have operated illegally.

- The final two scenarios consider a more specific set of circumstances. The first looks at the case in which there is one country with a very loose enforcement structure alongside one with a more rigid framework. The low enforcement country has a lower fine rate associated with IUU activity, severe capacity constraints and a reduced effectiveness of enforcement agents. Under these conditions, the long-run level of biomass in the low enforcement country is lower than in any of the other scenarios analysed. The share of fish caught illegally settles at around 45% in the low enforcement country and 40% in the higher enforcement country. These results highlight the negative externalities that are imposed on neighbouring coastal states when one country faces severe capacity issues which constrain it to low enforcement standards. This is particularly the case when there is a limited degree of border friction.

- The second bespoke scenario examines a situation in which there are two neighbouring coastal states with partial information sharing and similar enforcement standards, the only difference being that one of the countries imposes a more draconian fine rate on fishing vessels that are found to have conducted IUU activities. Border frictions are also introduced in this scenario, whereby only half of fishing vessels are able to move freely across the sea border, with the remaining fishing vessels confined to their home country's waters. The key finding from this scenario is that the primary beneficiary of a higher fine rate in country B is country A, where the share of fish caught illegally sinks to below 1% on average in the long run. This is because the higher fine rate in country B means that the strategy of conducting IUU activity in country A before landing the catch in country B (a common approach in scenarios where there is not full information sharing) is no longer viable for most fishing vessels. Another insight is that increased border frictions can support levels of biomass and reduce the prevalence of IUU fishing when there is not full information sharing between countries.

Table 1 Average level of biomass after 10,000 periods under various enforcement frameworks[1]

Level of biomass after 10,000 periods, average share of fish caught illegally during final 100 periods of simulations		Country B					
		10 enforcement agents, no information sharing, no capacity constraints		10 enforcement agents, partial information sharing, no capacity constraints		10 enforcement agents, full information sharing, no capacity constraints	
Country A	5 enforcement agents, no information sharing, no capacity constraints	93,654	89,383	99,916	113,636	106,404	123,712
	5 enforcement agents, partial information sharing, no capacity constraints			108,408	120,922		
	5 enforcement agents, full information sharing, no capacity constraints					134,815	138,403
	5 enforcement agents, full information sharing, minor capacity constraints					118,080	131,529
	5 enforcement agents, full information sharing, major capacity constraints					107,345	120,575

1 Values for country A in the left-hand cell and values for country B in the right-hand cell

	10 enforcement agents, no information sharing, no capacity constraints	93,237	92,884	102,184	111,825	114,158	128,319
	10 enforcement agents, partial information sharing, no capacity constraints			134,305	131,762		
	10 enforcement agents, full information sharing, no capacity constraints					144,235	144,196
	10 enforcement agents, full information sharing, minor capacity constraints					143,375	143,303
	10 enforcement agents, full information sharing, major capacity constraints					127,665	129,654

Table 2 Average share of fish caught over the final 100 periods that were caught illegally under various enforcement frameworks

Level of biomass after 10,000 periods, average share of fish caught illegally during final 100 periods of simulations		Country B					
		10 enforcement agents, no information sharing, no capacity constraints		10 enforcement agents, partial information sharing, no capacity constraints		10 enforcement agents, full information sharing, no capacity constraints	
Country A	5 enforcement agents, no information sharing, no capacity constraints	41%	43%	43%	12%	37%	1%
	5 enforcement agents, partial information sharing, no capacity constraints			34%	10%		
	5 enforcement agents, full information sharing, no capacity constraints					9%	1%
	5 enforcement agents, full information sharing, minor capacity constraints					18%	1%
	5 enforcement agents, full information sharing, major capacity constraints					32%	9%
	10 enforcement agents, no information sharing, no capacity constraints	44%	42%	39%	16%	31%	1%
	10 enforcement agents, partial			6%	8%		

	information sharing, no capacity constraints						
	10 enforcement agents, full information sharing, no capacity constraints					0%	0%
	10 enforcement agents, full information sharing, minor capacity constraints					2%	1%
	10 enforcement agents, full information sharing, major capacity constraints					10%	9%

1. Introduction

Many of the world's marine ecosystems are in a highly precarious position, with over-fishing representing one of the most prominent threats. Decades of population growth and rising living standards in the latter half of the twentieth century have caused the demand for marine fish to soar, while technological and geopolitical developments have simultaneously expanded the supply-side capacity of the global fishing fleet. These shifts in the fishing industry have had a pernicious impact on the underlying biological systems upon which the industry is built. The United Nation's (UN) Food and Agriculture Organisation (FAO) estimates that more than a third of the world's fish stocks were at biologically unsustainable levels as of 2017. This figure was less than 10% just forty years previously.

The scale of this issue has been recognised by many countries and inter-governmental organisations. Indeed, the United Nation's 14th Sustainable Development Goal is to:

"Conserve and sustainably use the oceans, seas and marine resources"

One of the major obstacles to achieving this goal is the presence of illegal, unregulated, and unreported (IUU) fishing activities, which undermine the various conservation policies that may be in place to promote the health of fisheries. The illicit nature of these activities means that the full extent of the issue is difficult to estimate precisely. However, the evidence suggests that IUU activity is a common and, in some cases, ubiquitous part of the fishing industry. The Sea Around Us project[2] finds that the Western Pacific Region of Asia is the part of the world with the highest volume of unreported fishing catch. An estimated 34% of the total catch in this region is unreported. Meanwhile in the Eastern Atlantic region, the majority of catch is thought to be unreported.

In essence, IUU fishing represents an economic problem, in so far as the perpetrators are economic agents seeking to maximise their expected profits. Cebr's 2018 report for The Pew Charitable Trusts titled "An agent-based model of illegal fishing" examines the incentives at play in the fishing market through the development of an agent-based model (ABM), which simulates the actions and interactions of individual fishing agents and enforcement agents within a wider biological and regulatory framework. This prior research focussed on two key enforcement tools that policymakers have at their disposal: the fine rate imposed on fishing vessels that are found to have been operating illegally, and the effectiveness of enforcement agents (as measured by the size of the area around them in which they are able to detect IUU activities).

The hypothesis was that altering these enforcement parameters would deter IUU fishing by reducing the expected profits relative to legal fishing activities, either due to an increased risk of detection or a tougher penalty in the event of detection. The results of the modelling showed that increasing the fine rate or expanding enforcement agents' radius of vision did significantly lower rates of IUU fishing in the model, although in most cases a sizeable share of fishing vessels continued to operate illegally. In the agent-based model, fishing vessels faced lower variable costs when conducting IUU activities, which created the incentive for some to operate illegally despite the risk of sanctions. The variation in the cost function between legal and IUU activities meant that the quantity of fish caught tended to be higher among fishing vessels operating illegally. As such, policies that reduced the prevalence of IUU fishing in the model were also effective in increasing the size of the fish population.

2 http://www.seaaroundus.org/

The internationalisation of the global fishing fleet means that co-operation between states is fundamental to the effective management of fisheries. Without this co-operation, authorities are unable to effectively police fishing vessels that land fish caught in another jurisdiction in one of their ports. This is true regardless of the levels of enforcement that are in force in any individual country. The FAO's Port State Measures Agreement – which came into force in 2016 – seeks to promote more information sharing between countries, particularly port states, so as to create a more effective deterrent for IUU activity for fishing vessels that operate across multiple sea borders. In any strategic interaction, an important consideration is the impact that one party's actions have on other parties. Therefore, a key area of interest in this research is the way in which the benefits (and costs) of information sharing are distributed between the country sharing the information and the country receiving the information.

The research presented in this report evaluates the degree to which information sharing regarding IUU activity between neighbouring countries affects:

- The health of the shared fishery, as measured by the level of biomass;
- The probability of being detected after conducting IUU activities;
- The prevalence of IUU fishing, as measured by the share of fish caught illegally and the characteristics of the fishing fleet;
- The revenues generated by each country through the imposition of fines upon fishing vessels that are found to have operated illegally, and;
- The fishery yield, as measured by the level of biomass extracted both cumulatively and in individual periods.

To do this, the ABM described previously has been augmented in the following ways:

- **Micro-foundations:** the plankton-consuming fish agents in the original model have been replaced by a biomass parameter capturing the health of the fish population;

- **Introduction of ports:** almost all fish caught in the ocean pass through ports. This is one of the characteristics that distinguishes the fishing supply chain from those in other industries. The existence of such "chokepoints" partially compensates for the regulatory challenges associated with the sea-based nature of fishing activities. It is also fundamental in shaping the intensity of fishing in certain patches of ocean, with activity typically more concentrated closer to ports. To capture this important component of the fishing industry, ports have been added to the ABM. The role of these ports in the model is as an exclusive location for fishing vessels to land their catch as well as a destination for information from enforcement agents surrounding IUU activities

- **Expansion to a two-country system:** the single-country framework in the previous tranche of research has been expanded to a two-country framework. This is necessary in order to model flows of information across sea-borders and examine to corresponding economic and biological impacts of this information sharing. Modelling a two-country system also allows for the effects of regulatory divergence between jurisdictions to be analysed.

- **Introduction of information sharing as a policy parameter:** the central goal of the research is to analyse how information sharing between enforcement agents in one country and the port of another country can affect outcomes in the model environment, such as levels of biomass and the share of fish that are caught illegally in either country. In the model, enforcement agents patrol their jurisdiction, taking note of any fishing vessels within their territory and radius of vision that are conducting IUU activities. This information can then be shared with the port in the neighbouring country if the relevant fishing vessels cross the border to land their catch.

- **Imposition of capacity constraints at ports:** another addition to the model is the introduction of capacity constraints at ports, which captures how technological, institutional or logistical barriers may prevent ports from imposing sanctions for IUU activities, even when the information is received that fishing vessels have been operating illegally.

The agent-based modelling approach offers numerous benefits in the context of analysing IUU fishing activities. It firstly allows for heterogeneity between economic agents, which facilitates the modelling of systems in which participants have varying characteristics and preferences. In this case, the model incorporated differing levels of aversion to IUU activity within the population of fishing vessels. The ABM also allows the notion of path dependency to be explored, by ensuring that agents' present decisions and preferences are informed by their past experiences and observations.

The remainder of this report is structured as follows: Section 2 provides an overview of the health of the world's fisheries, the issue of IUU fishing generally, and the role of information sharing as a potential solution to this challenge. Section 3 then describes the modelling methodology in greater detail, with a focus on the extensions that have been added since the original tranche of research. Section 4 presents the results of the modelling simulations, which test the effectiveness of varying levels of information sharing in a number of different regulatory contexts. Finally, section 5 discusses the key findings from the research, the corresponding policy implications, and further ways in which the ABM methodology can be deployed to provide insights into the management of fisheries worldwide.

2. Illegal, unreported and unregulated fishing in the world's fisheries

A comprehensive overview of the state of the world's fisheries with a focus on the issue of illegal, unreported and unregulated (IUU) fishing was conducted by Cebr in early 2018 as part of the report titled "An agent-based model of illegal fishing". This section revisits this earlier analysis, looking in particular at any developments that have taken place in the subsequent two years. The key theme of this iteration of the research is the potential impact of information sharing as a means of deterring IUU fishing. Accordingly, this section also includes a more in-depth discussion centred around the Port State Measures Agreement, which represents the most meaningful and largescale framework within which countries can share information on IUU activity.

2.1 The state of the world's fisheries

Global marine capture

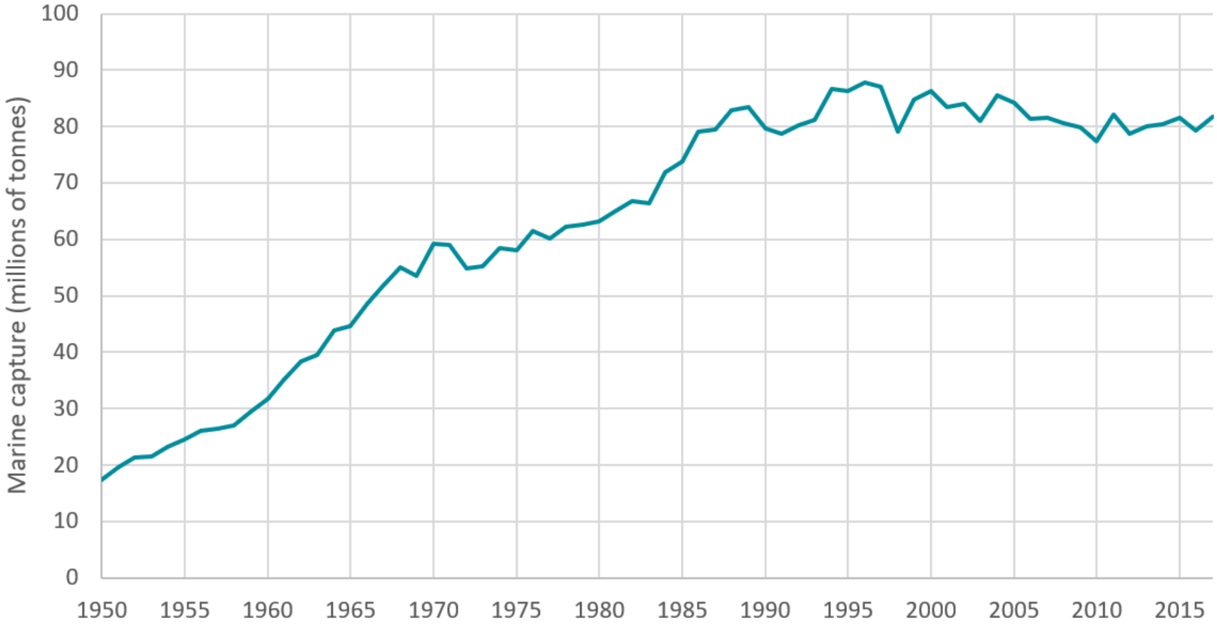
Data from the United Nation's (UN) Food and Agriculture Organisation (FAO) shows that fishing activity in the world's oceans rose swiftly and consistently in the latter half of the twentieth century. Indeed, between 1950 and 1996, global marine capture rose from 17.3 million tonnes to 87.7 million tonnes. This was driven by an array of factors including global population growth, increases in standards of living, technological progress and the importance of fish as a protein source for consumption.[3] Global marine capture edged down between the mid-1990s and 2010 and has since remained broadly stable. This trend from the 1990s may have partially been driven by the dissolution of the Soviet Union, and corresponding reduction in distant-water fleet activities.[4] In 2017 (the most recent year for which data is available), global marine capture came in at 81.7 million tonnes. Research by Pauly et al.[5] seeks to reconstruct this historical data by incorporating estimates of unreported catch in different parts of the word. This suggests that total global catch peaked at 130 million tonnes in 1996 and has since been on a significantly steeper downward trajectory than that implied by the FAO's estimates. This is driven by a declining industrial catch which is only partially offset by an increasing artisanal catch.

3 Fish provide 2.9 billion people with 20% of their animal protein, and 4.5 billion people with 15% of their annual animal protein, per Phelps Bondaroff, Teale N., Reitano, Tuesday and van der Werf, Wietse (2015). 'The Illegal Fishing and Organized Crime Nexus: Illegal Fishing as Transnational Organized Crime." The Global Initiative Against Transnational Organized Crime and The Black Fish'.

4 FAO (2016) 'The State of World Fisheries and Aquaculture 2016: Contributing to food security and nutrition for all'.

5 Pauly, Daniel & Zeller, Dirk (2016): Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining

Figure 1 Global marine capture in millions of tonnes, 1950 - 2017



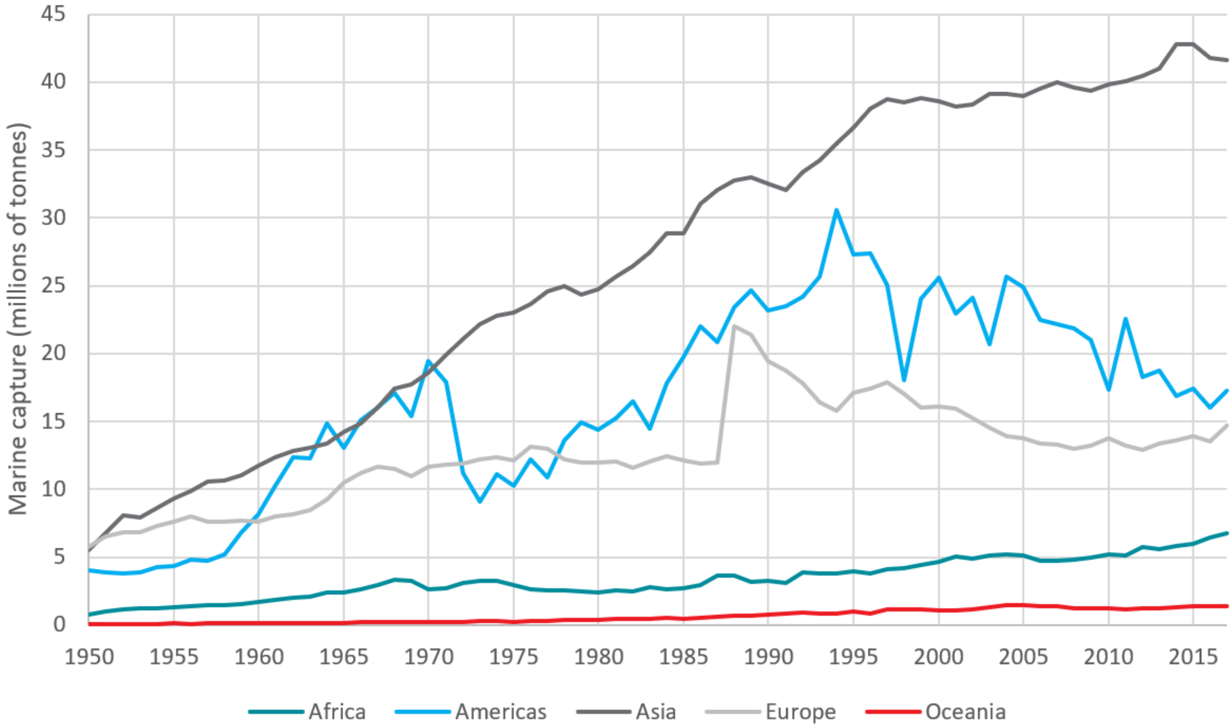
Source: FAO, Cebr analysis

Total marine capture varies significantly across different continents. Since 1950, Asia has been the continent with the largest marine capture in every year with the exception of 1964, 1966, 1967 and 1970 (in each of these years, the Americas accounted for a larger share of global marine capture). Between 1950 and 2017, Asia's marine capture has soared from 5.5 million tonnes to 41.6 million tonnes – a more than seven-fold increase. As of 2017, Asia accounted for 51% of global marine capture.

The Americas is the second largest continent in terms of marine capture, with 17.3 million tonnes landed in 2017. This represents just over a fifth (21%) of global marine capture. Marine capture in the Americas has been considerably more volatile than in Asia in recent decades. However, the general trend was one of increasing capture between 1950 and the early 1990s, followed by a steady decline in the years since. Similarly, Europe has recorded a gradual fall in marine capture since the mid to late 1980s, and as of 2017 the continent accounted for 19% of global marine capture. This is just over half the global share that Europe held in 1950.

Africa and Oceania are the continents that have experienced the most rapid growth in percentage terms since 1950. In Africa, marine capture has experienced a more than eight-fold increase since 1950, reaching 6.7 million tonnes in 2017. Meanwhile, marine capture in Oceania has risen from just 76,000 tonnes in 1950 to 1.4 million tonnes in 2017. The growth in Africa has been particularly pronounced in recent years. Indeed, between 2006 and 2017, marine capture in Africa has risen by nearly 44%.

Figure 2: Marine capture per continental region in million tonnes (1950-2017)



Source: FAO, Cebr analysis

There are valid concerns that the data on marine capture does not encompass the true extent of fishing activity, due to the presence of IUU fishing. Given its illicit nature, comprehensive and accurate measures of this are difficult, although it is estimated to be substantial. For example, between 2010 and 2011, China reported an annual catch in international waters of 368,000 tonnes, whereas fisheries experts estimate that the true catch was more likely close to 4.6 million tonnes per year.[6]

Sustainability of world fisheries

A fish stock is defined as being at biologically sustainable level if its abundance is at or above the level that can produce the maximum sustainable yield (MSY). This is "the largest average yield that can theoretically be taken from a species' stock over an indefinite period under constant environmental conditions".[7] Population growth is often modelled by the logistic growth function:[8]

6 Yap, Chuin-Wei, and Sameer Mohindru. 'China's Hunger for Fish Upsets Seas.' The Wall Street Journal (New York, USA), December 27, 2014.

7 https://www.pewtrusts.org/-/media/assets/2015/03/turning_the_tide_msy_explained.pdf

8 The logistic growth equation is one of many approaches that have been used in the literature to model fisheries.

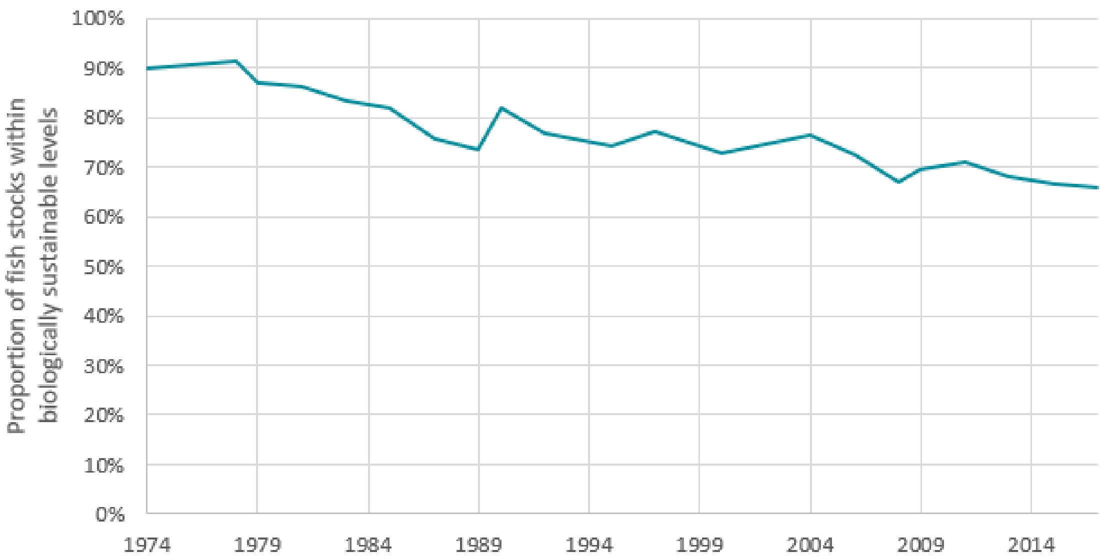
$$Population_{t+1} = Population_t + \{Population_t \times r \times (1 - \frac{Population_t}{Carrying\ capacity})\}$$

Equation 1 Logistic growth function

Where the carrying capacity is the maximum population level that the environment can support, and r is the species' intrinsic rate of growth. Differentiating this function with respect to the population level shows that the maximum population growth rate takes place when the population is equal to half the carrying capacity. This value also corresponds to the MSY.

While the increase in marine capture outlined above is not worrying in and of itself, what is concerning is the proportion of global fish stock not caught within biologically sustainable levels. Data from the FAO shows that the proportion of global fish stocks that are below the MSY level has fallen from 90% in 1974 to just under two thirds (66%) in 2017 (the latest year for which data is available). This means that in 2017, more than a third of global fish stocks were at a biologically unsustainable level, severely harming the long-term viability of these resources. Moreover, if the trend in the years leading up to 2017 were to have continued, the picture would now be even more troubling.

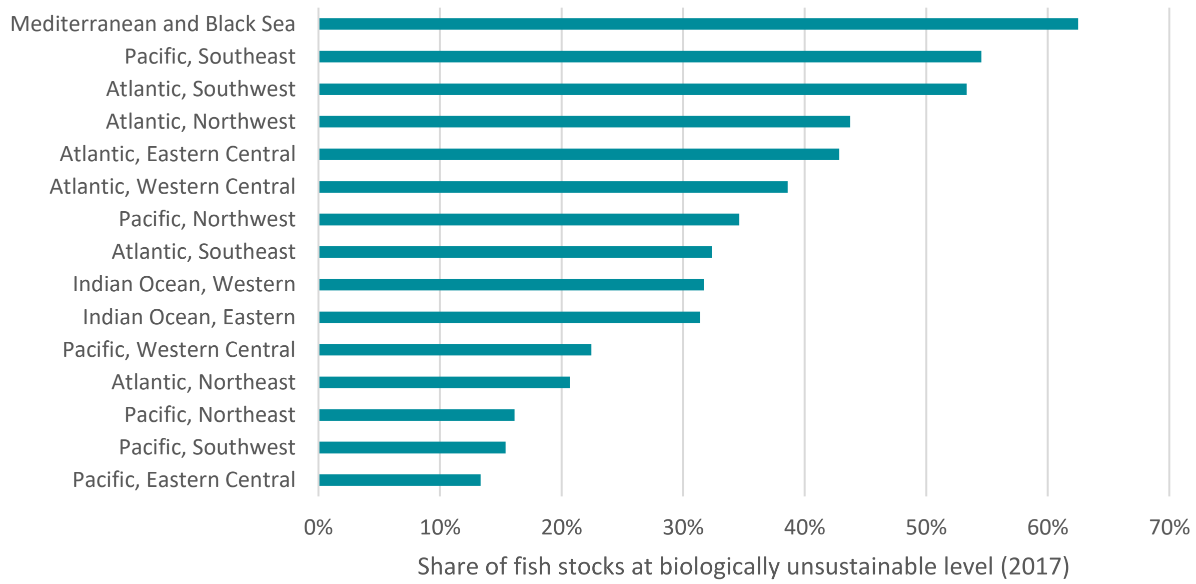
Figure 3: Proportion of global fish stocks within biologically sustainable levels (1974-2017)



Source: FAO, Cebr analysis

This data can be disaggregated to show the proportion of fish stocks at a biologically unsustainable level, broken down by oceanic area. This shows the clear variation in the sustainability of fish stocks in different parts of the world. Three regions stand out as having a particularly high proportion of their stock at an unsustainable level. These are the Mediterranean & Black Sea, the Southeast Pacific, and the Southwest Atlantic, which in 2017 had 62.5%, 54.5% and 53.3% of their fish stocks at biologically unsustainable levels, respectively. It is also notable that all oceanic areas have at least 10% of their fish stock at a biologically unsustainable level.

Figure 4 Share of fish stocks at a biologically unsustainable level, by oceanic region



Source: FAO, Cebr analysis

Hillborn et al.[9] find that the abundance of fish stocks is increasing in the roughly half of global fisheries for which reliable scientific assessments are available. Moreover, the research shows that fish stocks are generally improving or remaining at target levels in regions where fisheries are intensively managed. Examples of policy interventions that have helped to alleviate fishing pressures include the imposition of catch limits and development of rebuilding plans in the mid-1990s in the US and the introduction of total allowable catches for numerous species in Japan in 1997. The benefits of sustainable fishery management are not just environmental. Indeed, a 2016 study by Costello et al.[10] estimate that the application of effective management reforms in a sample of fisheries representing 78% of global reported catch could lead to $53 billion in additional profits each year.

2.2 An introduction to illegal, unreported and unregulated (IUU) fishing

Given the rising share of fish stocks at biologically unsustainable levels, it is vital that appropriate conservation and management practises are put in place to combat this trend. Illegal, unreported and unregulated (IUU) fishing activities represent a serious threat and can undermine these sustainable practises. IUU activities are defined as follows:

- **Illegal fishing** encompasses a broad range of actions by vessels that violate national laws and/or international agreements such as the conservation and management measures put in place by a Regional Fisheries Management Organisation (RFMO).

9 Hilborn, Ray et al. (2019): Effective fisheries management instrumental in improving fish stock status

10 Costello, Christopher et al. (2016): Global fishery prospects under contrasting management regimes

- **Unreported fishing** refers to the non-reporting or misreporting of information concerning fishing activity. Whilst this includes the misreporting of catches (both by volume and fish type), it may also include the misreporting of a broader range of activities relating to fishing. It may therefore include both the non-reporting of activities that are legal, but also those that violate national laws and/or RFMO conservation rules.

- **Unregulated fishing** principally concerns the activities of vessels that are either stateless or fly the flag of states that are not party to the relevant RFMO. It also includes fishing in areas for which there are no relevant conservation and management measures in place. In these instances, unregulated fishing can arise due to an absence of governance and regulation. There is ongoing debate about whether unregulated fishing should be defined alongside illegal and unreported fishing. This is on the grounds that illegal and unreported fishing represent legislative or regulatory breaches, while unregulated fishing reflects an absence of legislation or regulation.

The FAO's formal definitions of IUU fishing and its components are set out in Box 1.

Box 1: Formal definition of IUU Fishing

The FAO (2001) 'International Plan of Action to prevent, deter and eliminate illegal, unreported and unregulated fishing' formally defines IUU fishing as follows:

Illegal fishing concerns activities:

- "conducted by national or foreign vessels in waters under the jurisdiction of a State, without the permission of that State, or in contravention of its laws and regulations; or
- conducted by vessels flying the flag of States that are parties to a relevant regional fisheries management organization but operate in contravention of the conservation and management measures adopted by that organization and by which the States are bound, or relevant provisions of the applicable international law; or
- in violation of national laws or international obligations, including those undertaken by cooperating States to a relevant regional fisheries management organization."

Unreported fishing concerns activities:

- "which have not been reported, or have been misreported, to the relevant national authority, in contravention of national laws and regulations; or
- undertaken in the area of competence of a relevant regional fisheries management organization which have not been reported or have been misreported, in contravention of the reporting procedures of that organization."

Unregulated fishing concerns activities:

- "in the area of application of a relevant regional fisheries management organization that are conducted by vessels without nationality, or by those flying the flag of a State not party to that organization, or by a fishing entity, in a manner that is not consistent with or contravenes the conservation and management measures of that organization; or
- in areas or for fish stocks in relation to which there are no applicable conservation or management measures and where such fishing activities are conducted in a manner inconsistent with State responsibilities for the conservation of living marine resources under international law."

2.3 Drivers of IUU fishing

There are a variety of factors that may induce IUU fishing activities. In the original agent-based model, it was assumed that all fishing vessels made decisions with the sole consideration of maximising their expected profits. This assumption has been loosened somewhat in the latest tranche of modelling, to allow for varying levels of aversion to IUU activity. Despite this heterogeneity of preferences, each of the factors in Table 3 nonetheless have at least some influence on all fishing vessels.

Table 3: Factors that incentivise and facilitate IUU fishing

<table>
<tr><th>Factor</th><th>Details</th></tr>
<tr><td>Low probability of detection (risk)</td><td>The covert nature of IUU fishing means that it can be very difficult to detect. Indeed, a number of studies demonstrate that those engaging in IUU fishing are infrequently detected and penalised. The infrequency of detection may arise for a number of broad reasons:

Scale of operating environment: The sheer scale of the areas in which IUU vessels operate can make detection difficult.
Incomplete/non-exhaustive international agreements: International agreements may not fully account for the ways in which IUU activity may occur, thus providing gaps in enforcement for these activities.
Weak governance: The risk of being detected engaging in IUU activities is likely to be lower for vessels operating in the waters of coastal states and / or regions that have weak governance and institutions.
Varying levels of enforcement between countries: All states have a right to register ships, taking responsibility for ensuring that they act within international law. However, some states do not adequately follow through on this requirement. Registering with such states can make IUU fishing easier, due to reduced scrutiny, the ability to maintain anonymity, and the ability to exploit gaps in international regulation.
Corruption: If officials that are charged with monitoring fishing vessels and detecting IUU activities are corrupt, this reduces the risks associated with IUU fishing.
Transshipment. Transshipment often involves the transfer of a catch from a shipping vessel to a refrigerated cargo ship, which may then eventually land the catch at a distant port. This reduces the traceability of fish and thus reduces enforceability. Therefore, while transhipment can improve economic efficiency, it is also a potential facilitator of IUU fishing.
Inadequate monitoring technologies. In addition to the difficulties associated with traditional surveillance (such as patrol vessels), there may also be inadequate monitoring technologies in place. Examples of modern monitoring technologies include:[11]
- Automatic Identification Systems (AIS): vessels fitted with AIS transmitters electronically exchange data on identity, position and so forth with other vessels and authorities.
- Vessel monitoring/detection system (VMS, VDS): satellite monitoring of vessels with a typically more extensive coverage than AIS, although the data is not publicly shared.
- Electronic recording and reporting system (ERS): facilitates the recording and reporting of catches / general fishing activity.
</td></tr>
<tr><td>Higher returns</td><td>There are number of reasons as to why the returns to illegal fishing are high.</td></tr>
</table>

11 European Commission: 'Fisheries – Control technologies'.

Factor	Details
	• **Market price:** The fish being caught may attract a high market price. This is especially the case if the fish are rare or endangered and their catch is banned, or limited by a quota, as this acts to supress supply. • **Ignoring quantity restrictions:** Illegally catching more than permitted by quotas can also increase returns.
Lower costs	Operating costs equally can be lower for IUU fishing due to the following factors: • **Licensing:** Ignoring licensing requirements – which may require a cost to obtain – can increase profits. • **Regulation:** Subverting regulations can allow fishing in a cheaper (and often more ecologically damaging way), such as by bottom trawling or cyanide fishing. • **Entering closed areas:** Entering closed fishing areas may be more efficient, for instance if they are closer to ports. If IUU activities entail any additional costs (such as the bribery of officials), this is typically more than offset by other factors mentioned above.[12]
Sanctions	The sanctions imposed on a vessel that has been found to have engaged in IUU fishing may be insufficient to deter such behaviour. In particular, deterrence will depend on the extent to which the fine is proportional to the benefits of the IUU activity.
Few barriers to entry	Any additional costs and / or skills required to engage in IUU fishing may be negligible. For example, registering under a flag of non-compliance is typically quick and easy, and vessels can re-flag and change names easily.

Another relevant dynamic that affects the prevalence of IUU fishing is the emergence of positive feedback loops, whereby an increase in IUU fishing eventually spreads to other fishers.[13] IUU fishers sell their products in the same market as legal fishers, and often are able to do so at a lower cost due some of the factors outlined in Table 3. This may force fishers who otherwise would have fished in a legitimate manner to engage in IUU fishing activities simply to remain competitive. Equally, if IUU fishing triggers regulatory responses (such as the imposition of quotas as fish stocks suffer), this may also harm the bottom line of legitimate fishers and increase the incentive for them to engage in IUU practises. A high prevalence of IUU fishing activities also has the potential to alter the characteristics and behaviours of fishing vessels that have historically operated in a legal manner, due to the formation of social and business “norms” or an erosion of respect towards regulatory frameworks and institutions.

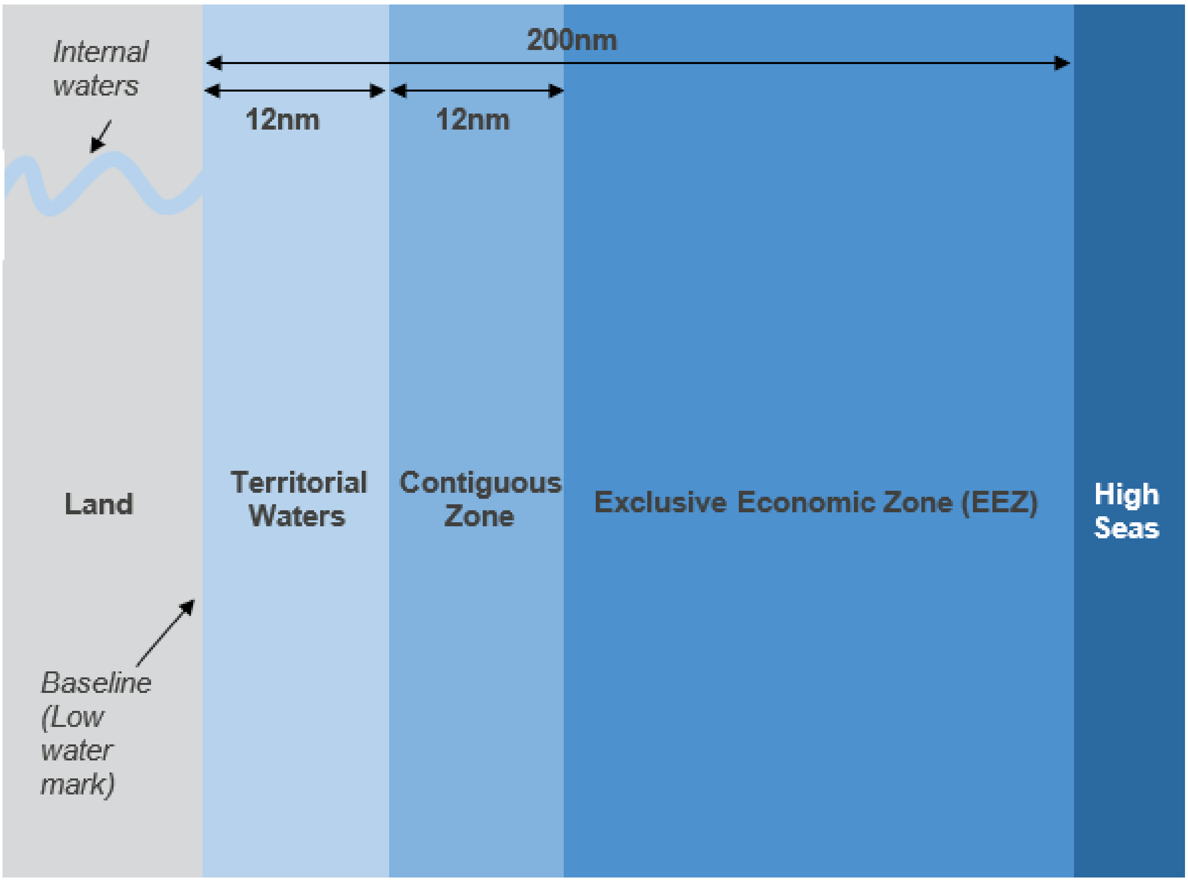
12 OECD. (2005). ‘Why fish piracy persists: The economics of Illegal, Unreported and Unregulated fishing’.

13 The Global Initiative Against Transnational Organized Crime and The Black Fish. (2015). ‘The Illegal Fishing and Organized Crime Nexus: Illegal Fishing as Transnational Organized Crime’.

2.4 Structure of the sea as defined by international law

This section outlines the zones of the sea, as defined by international law, and by extension the areas where IUU fishing may occur. The structure of the sea is set out diagrammatically below.

Figure 5 Structure of the sea, as defined by international law



Source: European Maritime Safety Agency, Cebr

As shown in Figure 5, a coastal state has some degree of sovereign rights over an area extending out 200 nautical miles (nm) from the coastline. The relative level of influence that the coastal state has increases as you get closer to the shore. Specifically, the territorial waters and contiguous zones (0-12 nm from the shore and 12.1-24 nm from the shore, respectively) are legislated differently to the Exclusive Economic Zone, per the 1982 United Nations Convention on the Law of the Sea (UNCLOS).

Internal waters

States typically maintain full territorial sovereignty over internal waters, allowing them to impose their own regulations, customs and immigration laws. The classification of internal waters, as set out in Article 8 of UNCLOS[14], can be summarised as follows:

14 United Nations. (1982). 'United Nations Convention on the Law of the Sea'.

- Waters on the landward side of the baseline of the territorial waters represent a nation's internal waters.
- Where the establishment of this baseline encloses waters which previously had not been considered internal, 'right of innocent passage' continues to exist through this area.

Territorial Waters

Countries maintain full territorial sovereignty in this region, except for the fact they have to allow innocent passage. This is explained in more detail in Articles 17-19 of UNCLOS[15]:

- Per Article 17, 'right of innocent passage' allows ships of all states (whether coastal or land-locked) innocent passage through the area.
- Per Article 18' 'passage' refers to continuous and expeditious travel through the sea for the purpose of either traversing the sea without entering internal waters, calling at a roadstead/port facility outside internal waters, or proceeding to or from internal waters or a call at a roadstead/port facility.
- Per Article 19, passage is innocent so long as it is not prejudicial to the peace or security of the coastal state.

Contiguous Zone

In the contiguous zone, the coastal state has more power to enforce its customs, fiscal and immigration regulations than they would in the EEZ but not full sovereignty as in the territorial waters. This is set out in Article 33 of UNCLOS, which outlines that in this zone, the coastal state maintains a level of control necessary to prevent and punish infringement of its customs, fiscal, immigration, and sanitary laws and regulations.

Exclusive Economic Zone

The coastal state has sovereign rights over the exclusive economic zone (EEZ) with regard to exploring, exploiting, conservation, and management. Article 61 of UNCLOS stipulates that the coastal state sets the allowable catch of a given type of living resource and has the responsibility to ensure that species are harvested at levels consistent with producing the maximum sustainable yield. In addition to scientific evidence, economic considerations including the needs of coastal fishing communities are given weight in determining the conservation measures. In cases where the coastal state has insufficient capacity to fully harvest the allowable catch that they have set, they may permit vessels from other states to have access to the remaining surplus. Importantly, however, vessels from states other than the coastal state must comply with the laws and regulations that the coastal state has in place.

15 United Nations. (1982). 'United Nations Convention on the Law of the Sea'.

Table 4: Examples of laws and regulations that a coastal state may apply

Laws and Regulations	Description
Licensing	Fishing vessels, fishermen and equipment may be required to be licensed.
Catches	The coastal state may set a series of quotas across the fish species that are allowed to be harvested. These quotas may take the form of a maximum catch per vessel over a period of time. Further restrictions can also be imposed which set the permissible levels of bycatch (fish caught unintentionally) and discards (parts of the catch that are returned to sea).
Fish types	It may not be permitted to catch certain species of fish. Of species that can be caught, there may be restrictions on both size and age.
Seasonal restrictions	Fishing of a given species may not be permitted in some seasons.
Equipment use	Restrictions may be in place on the type, size and quantity of gear and vessels that can be used.
Ports	Vessels may be required to land a proportion of their catch in a port of the coastal state and be subject to the relevant checks and audits.
Information requirements	Certain information may be required from fishing boats including vessel position, movement, catch and effort statistics. For example, vessels may be required to have fitted a satellite tracking device for the purposes of implementing a vessel monitoring system (VMS). In addition, vessels may also need to have an automatic identification system (AIS) installed, so as to automatically exchange data with proximate ships and authorities.

Source: United Nations (1982), Cebr Analysis

To illustrate the importance enforcing conservation and management operations within EEZs, note that while EEZs on aggregate only account for approximately 35% of total sea area, they account for 90% of the world's fish stocks.[16] The present system of EEZs only came into force in the 1970s, and it added vast areas of space for countries to regulate. As previously discussed, the sheer scale of EEZs can bring enforcement challenges for many countries.

The High Seas

All states (coastal and land-locked) have freedom to access the high seas. Articles 117 and 118[17] of the UNCLOS requires cooperation between states to ensure the conservation and management of living resources. In particular, states that seek to exploit the same area or resources of the high seas must negotiate to ensure the appropriate conservation measures are in place. With regard to these conservation measures, Article 119 of the UNCLOS stipulates that states put measures in place to ensure that fish species are harvested at a rate that can produce the MSY, using the best available scientific evidence. This may be achieved through the formation of Regional Fishing Management Organisations (RMFOs), which are explained in more detail in the next section.

16 European Parliament. (2017). 'International fisheries relations'.

17 United Nations. (1982). 'United Nations Convention on the Law of the Sea'.

2.5 Regional Fisheries Management Organisations (RFMOs)

States that have fishing interests in a particular area of the high seas may choose to form Regional Fisheries Management Organisations (RFMOs). These are international organisations that aim to manage fish species and stocks in a given area. While the extent of powers varies across different RFMOs, the majority have legal powers to determine and enforce regulations, including fishing effort and catch restrictions.[18] RFMOs can thus be seen an important mechanism through which states can meet their obligations in the high seas as set out by UNCLOS Articles 117 and 118.

RFMOs are present in the majority of high sea regions with major deep-sea fisheries.[19] While some RFMOs play a more advisory role, most possess at least some legal powers. The class of RFMOs with legal powers can be broken down into three broad categories:[20]

- **General RFMOs:** as the name suggests, general RFMOs have a mandate that applies to a broad range of species. In some cases, the scope is sufficiently broad that exceptions only apply to species that are protected or managed under other international agreements. There are eight General RFMOs, ranging from North East Atlantic Fisheries Commission (NEAFC) formed in 1982 to the North Pacific Fisheries Commission (NPFC) formed more recently in 2015.
- **Highly migratory species (Tuna) RFMOs:** general RFMOs may not be appropriate for certain highly-migratory species – specifically tuna or tuna-like species[21] – due to the scale

18 European Commission. 'Regional fisheries management organisations (RFMOs)'.

19 FAO. (2017). "Regional fisheries management organisation and deep-sea fisheries", http://www.fao.org/fishery/topic/166304/en

20 Asmundsson, S. (2016). 'Regional Fisheries Management Organisations (RFMOs): Who are they, what is their geographic coverage on the high seas and which ones should be considered as General RFMOs, Tuna RFMOs and Specialised RFMOs?'

21 Annex I of UNCLOS (1982, p.145) defines a list of seventeen highly migratory species; almost half of which are tuna. They are as follows: Albacore tuna (*Thunnus alalunga*); Bluefin tuna (*Thunnus thynnus*); Bigeye tuna (*Thunnus obesus*); Skipjack tuna (*Katsuwonus pelamis*); Yellowfin tuna (*Thunnus albacares)* ; Blackfin tuna (*Thunnus atlanticus)*; Little tuna (*Euthynnus affinis, Euthynnus alletteratus)*; Southern Bluefin tuna (*Thunnus maccoyii*); Frigate mackerel (*Auxis thazard, Auxis rochei)*; in addition to Pomfrets; Marlins; Sail-fishes; Swordfish; Sauries; Dolphin; Oceanic sharks; and Cetaceans.

The differing characteristics of tuna species render them more or less vulnerable to overfishing. On the one hand, Skipjack tuna are less susceptible to overfishing due to their high fecundity (fertility/reproductive rate), short-lifespan and are wide distribution across both tropical and temperate waters. On the other hand, the reproductive and well-defined migration properties of Bluefin tuna makes them more susceptible to overfishing (See Maguire, J.-J.; Sissenwine, M.; Csirke, J.; Grainger, R.; Garcia, S. (2006). 'The state of world highly migratory, straddling and other high seas fishery resources and associated species'.

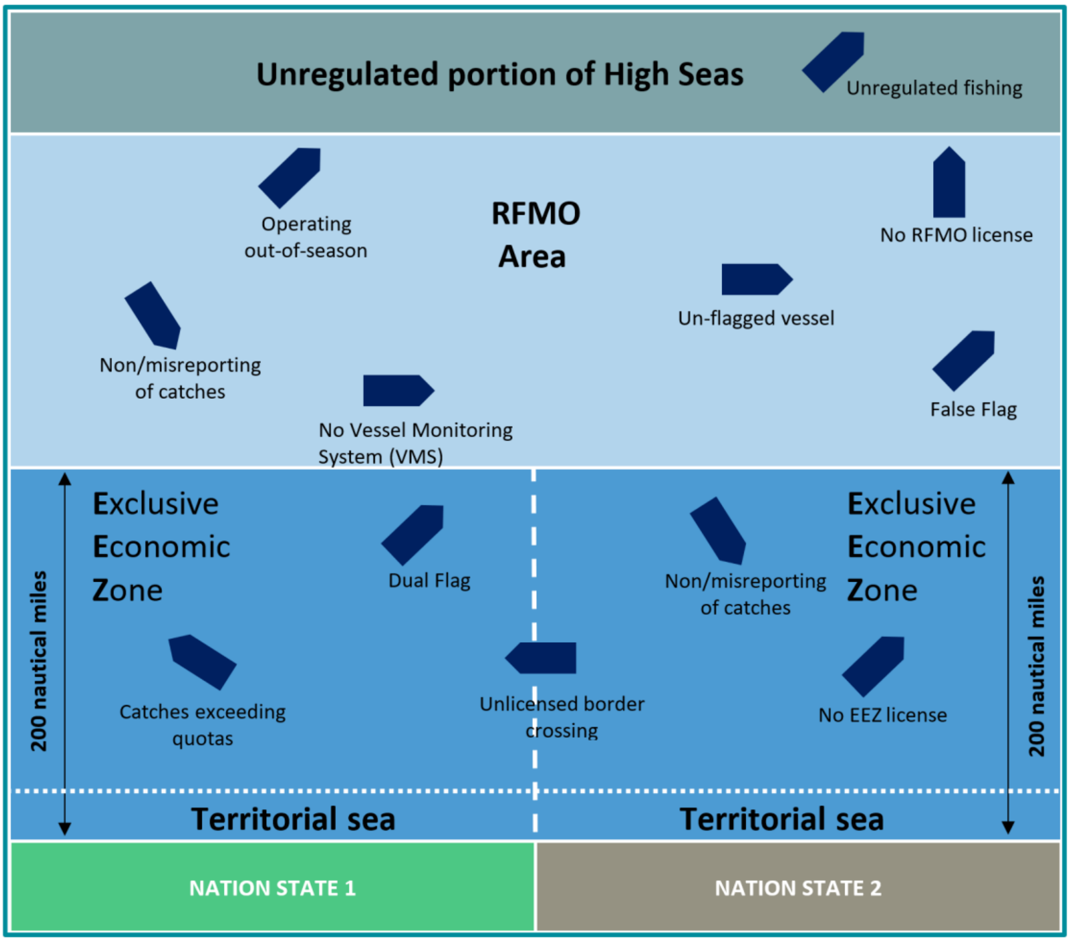
of the management body required. As such, a number of "Tuna" RFMOs exist to help implement conservation and management practices over large areas.

- **Specialised RFMOs:** analogous to highly migratory species RFMOs, specialised RFMOs have a narrower legal definition than general RFMOs, and deal with specific fisheries' species.

2.6 Types of IUU Fishing

Figure 6 illustrates some of the types of IUU fishing that vessels could engage in, depending on whether they are in an EEZ, and RFMO area, or an unregulated portion of the high seas. The diagram consists of two coastal states, which each have an EEZ in which they can set enforceable conservation and management measures to combat IUU fishing. Beyond the respective EEZs are the high seas, which may or may not be regulated through RFMOs.

Figure 6 Types of IUU fishing



Sources: Lee and Funge-Smith (2015),[22] National Intelligence Council (2016), Cebr Analysis

22 Lee, R., and Funge-Smith, S. (2015) 'Update on combating illegal fishing in Asia'.

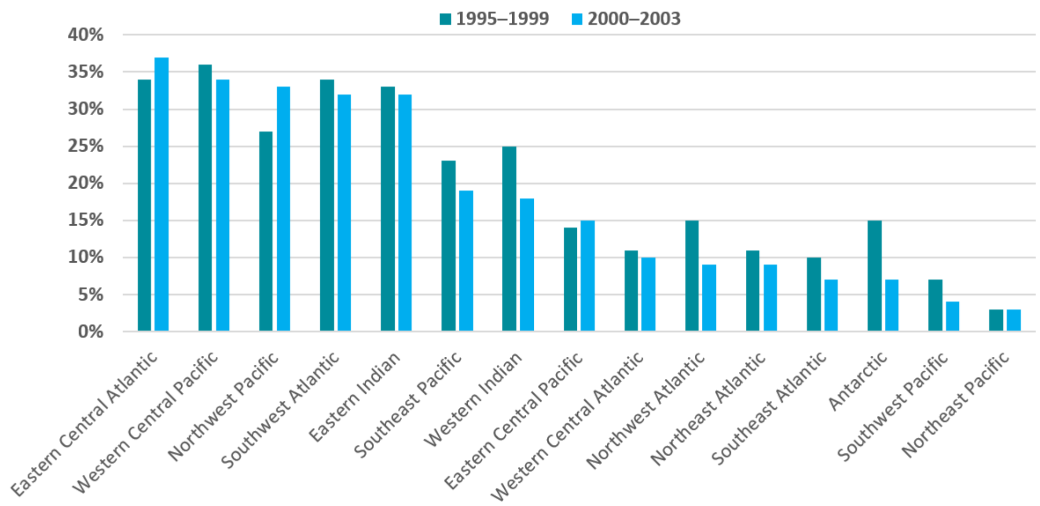
2.7 Prevalence of IUU fishing and regions particularly affected

Reliably assessing the extent of IUU fishing in a standardised manner is a formidable undertaking, given its clandestine nature and the inherent data limitations that come with this. Attempts have been made in specific markets and regions, but less so at an overarching level. This section provides an overview of the information available that provides some indication of the pervasiveness of the issue of IUU fishing.

Academic literature

In the academic literature, the most widely referenced paper is the 2009 study 'Estimating the Worldwide Extent of Illegal Fishing'.[23] This estimates the global level of illegal and unreported catches at between 11 and 26 million tonnes, with a value each year of $10 billion - $23.5 billion. In this analysis, the prevalence of illegal fishing did not display a significant relationship with the price of fish, the size of the EEZ, or the size of the fishery itself. It did, however, find that less well governed states are more prone to IUU fishing.[24] Intuitively, this result is not surprising. In addition to affecting the behaviour of domestic fishing vessels, low levels of governance may also induce international ships to register with a 'flag of convenience' to use the laxer regulations in that country to their benefit. In this way, not only do poorly governed countries tend to be associated with increased illegal fishing, but their poor governance also tends to attract illegal fishers to their waters. Limitations of this study include the reliance on data from 2005, broad estimates of the scale of the IUU fishing industry, and a lack of country-specific estimates.

Figure 7 The percentage of catches in each FAO fishing area that is illegal, averaged over five-year periods



Source: Agnew et al (2009), Cebr analysis

23 Agnew, D et al. (2009). ['Estimating the Worldwide Extent of Illegal Fishing'.]

24 A significant correlation was found between Governance indicators from the World Bank and the extent of illegal fishing.

Another key piece of literature is the 2016 paper 'Towards the Quantification of Illegal, Unreported and Unregulated (IUU) Fishing in the Pacific Islands Region', released by MRAG Asia Pacific. The study involves a bottom-up analysis of activity in the Western and Central Pacific region, in an attempt to quantify the volume and value of IUU fishing. In their discussion of IUU fishing, the practice is split into four main types of activity: unlicensed fishing, misreporting (including under-reporting and misidentification), non-compliance with licence conditions, and post-harvest activity. The modelling suggests that the total volume of product harvested through IUU activity each year is 306,440 tonnes, with a 90% confidence that the figure lay within the interval of 276,546 tonnes and 338,475 tonnes. In terms of value, the findings estimate an annual figure of $616.11 million. Within this overall figure, the largest contribution stems from misreporting, with the annual volume and value estimated at 167,341 tonnes and $313.42 million, respectively.

The paper also considers the costs to Pacific Island countries, as measured by the earnings the country could otherwise have received in the absence of IUU practices, under the assumption that IUU fishing vessels do not pay licensing fees. It is suggested that fishing vessels' profits over and above the normal profit level could be expected to be returned to the coastal states since, in a competitive market, this represents the maximum fee a vessel could be expected to pay for a license granting it permission to conduct fishing operations. Based on this methodology, it is estimated that the total losses to Pacific Island countries from IUU practices stand at $152.67 million each year. However, it is important to acknowledge that the assumption of perfectly competitive markets and efficient licensing systems that these calculations are grounded upon rarely exist in reality.

The paper concludes with suggestions on measures that can be taken to disincentivise, and hence reduce, the prevalence of IUU fishing. Its suggestions include a strengthening of catch monitoring, the introduction of electronic monitoring of vessels, and independent verification of fishing activity. As a bottom-up analysis, the study's findings are highly specific to the Pacific Island region, relying extensively on detailed, local information. As such, there should be caution about extrapolating the findings to other contexts. Other methodological concerns stem from the timescales involved. The availability and precision of the data used varies in precision and availability over different time periods. Data varied in precision and availability over different time periods. This means that, instead of using a consistent timeframe for the categories of IUU fishing, different time periods of the same length were used for each category and subsequently taken as a benchmark estimate of a typical period.

The Sea Around Us

The Sea Around Us research initiative[25] uses FAO data as a baseline to reconstruct official catch data to develop estimates of the levels of unreported catches. These estimates make use of a range of data sources such as local experts, grey literature and historical records.[26]

Table 5 indicates that the Western Pacific Region of Asia is the oceanic area with the highest volume of unreported catches. The region of the Atlantic off the coast of West Africa is the next largest area for unreported fishing. In this portion of the Atlantic, the reported and unreported tonnages are very similar in magnitude.

25 http://www.seaaroundus.org/

26 For an exact definition of the Fishing Areas see http://www.fao.org/fishery/area/search/en

Table 5 Tonnage of reported and unreported catch in 2014, by FAO area

	Tonnage of reported catch, 2014 (000s)	Tonnage of unreported catch, 2014 (000s)	Regional share of unreported catch
Pacific, Northwest	22,797	5,649	20%
Pacific, Western Central	11,644	6,050	34%
Atlantic, Eastern Central	4,843	5,067	51%
Atlantic, Northeast	8,473	1,013	11%
Indian Ocean, Eastern	6,140	2,997	33%
Pacific, Southeast	7,306	1,796	20%
Indian Ocean, Western	3,606	2,137	37%
Atlantic, Southwest	2,543	908	26%
Pacific, Eastern Central	2,368	856	27%
Pacific, Northeast	2,405	109	4%
Mediterranean & Black Sea	1,316	1,069	45%
Atlantic, Northwest	1,827	495	21%
Atlantic, Western Central	1,284	843	40%
Atlantic, Southeast	1,554	555	26%
Pacific, Southwest	498	189	28%
Atlantic, Antarctic	297	29	9%
Indian Ocean, Antarctic	12	-	0%
Arctic Sea	-	10	100%

IUU Fishing Index

The IUU Fishing Index was developed by Poseidon Aquatic Resource Management Ltd. and the Global Initiative Against Transnational Organised Crime in an attempt to benchmark countries based on their exposure and response to IUU fishing.[27] While it does not attempt to calculate the volume of IUU fishing, it is a useful proxy for the prevalence of IUU fishing in each country.

Countries are assigned a score from 1-5 given for a total of 40 indicators. 1 represents good/strong performance, whereas 5 represents bad/weak performance. The 40 indicators are grouped into the following categories:

- Vulnerability – Indicators related to the risk of IUU fishing occurrence
- Prevalence – Indicators related to known IUU incidents.
- Response – Indicators related to actions set out to reduce IUU fishing.

The indicators are also assigned to the following groups:

- Coastal – Indicators related to states' obligations in managing their EEZ.
- Flag – Indicators related to states' obligations relating to the specific vessels they flag.
- Port – Indicators related to states' obligations relating to port control and responsibilities.
- 'General' – Indicators that are not related to specific to the above three categories, such as market-related and sector wide indicators.[28]

One drawback of the Index is that, owing to difficulties in obtaining reliable data on matters related to IUU fishing, much of the ranking of countries' performance stems from value judgements or subjective analyses. Another potential issue is the complete separation of measures of vulnerability, prevalence, and response, when in many cases it is appropriate to consider the categories holistically. For instance, it could be argued that the level of response to IUU fishing practices should be assessed relative to the country's vulnerability, such that a country with a weak response but also a low vulnerability to IUU fishing would be rated less harshly than a country with the same response but a higher vulnerability. Despite the aforementioned methodological questions, the Index nonetheless provides a useful benchmark through which to compare the state of IUU fishing between countries, regions, and geographical areas, as well as their progress on this matter over time.

Looking at the Index measures at both a regional and country-specific level, Europe exhibits the best performance. Eight of the top ten best-performing states are European, while the continent-wide score of 2.05 places Europe above North America as the best region in combating IUU practices. As a region, Asia scores particularly poorly in the Index. The worst scores are exhibited by China, Taiwan and the Association of Southeast Asian Nations (ASEAN) countries generally.[29] Indeed, the combined China, Taiwan and ASEAN average Index score is higher for each of the respective indicator groups than the world average, which corresponds to a worse performance. This shows not only that the region is particularly vulnerable to IUU fishing, but also that the response to the problem is currently ineffective and that IUU fishing is therefore likely occurring at a high rate. This represents a serious threat to

27 http://www.iuufishingindex.net/about

28 http://www.iuufishingindex.net/methodology

29 These are Singapore, Thailand, Cambodia, Indonesia, Myanmar, Malaysia, Vietnam, the Philippines, Brunei, Timor-Leste and Laos. Data is not available for Laos, and as such it has not been included in the analysis.

the long-term fishing stocks of the two ocean basins which the ASEAN nations overlap (the East Indian and Western Pacific basins).

Figure 8 IUU Fishing Index Performance across major geographical regions

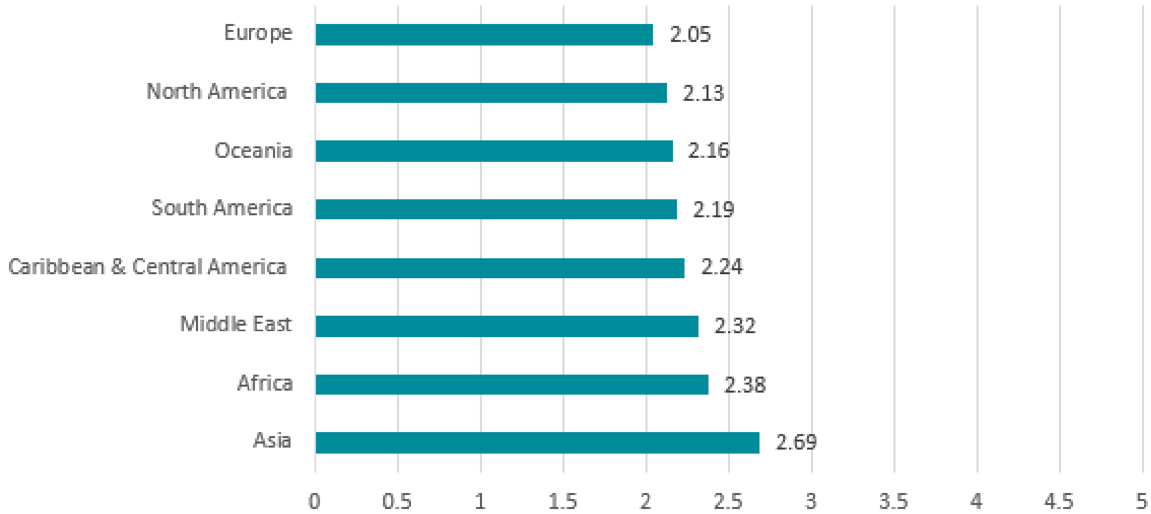
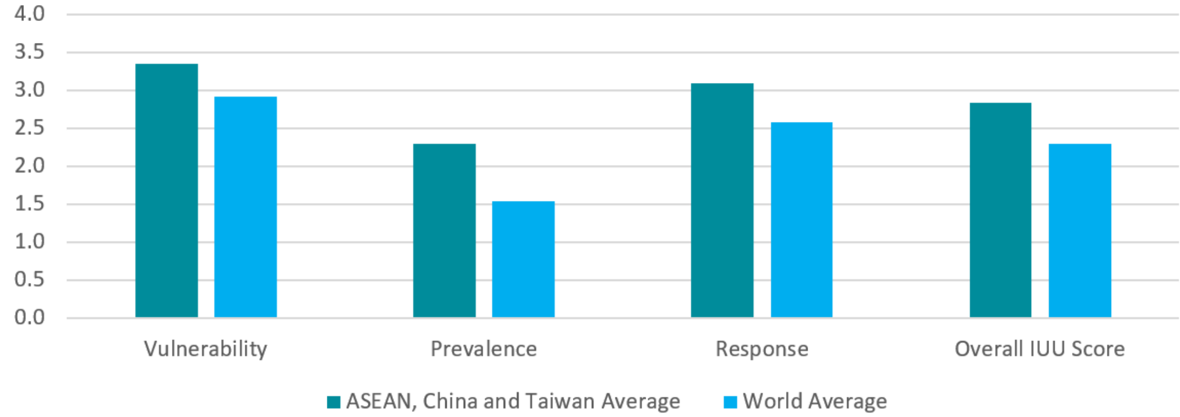


Figure 9: China, Taiwan and ASEAN average IUU Fishing Index performance compared to global average



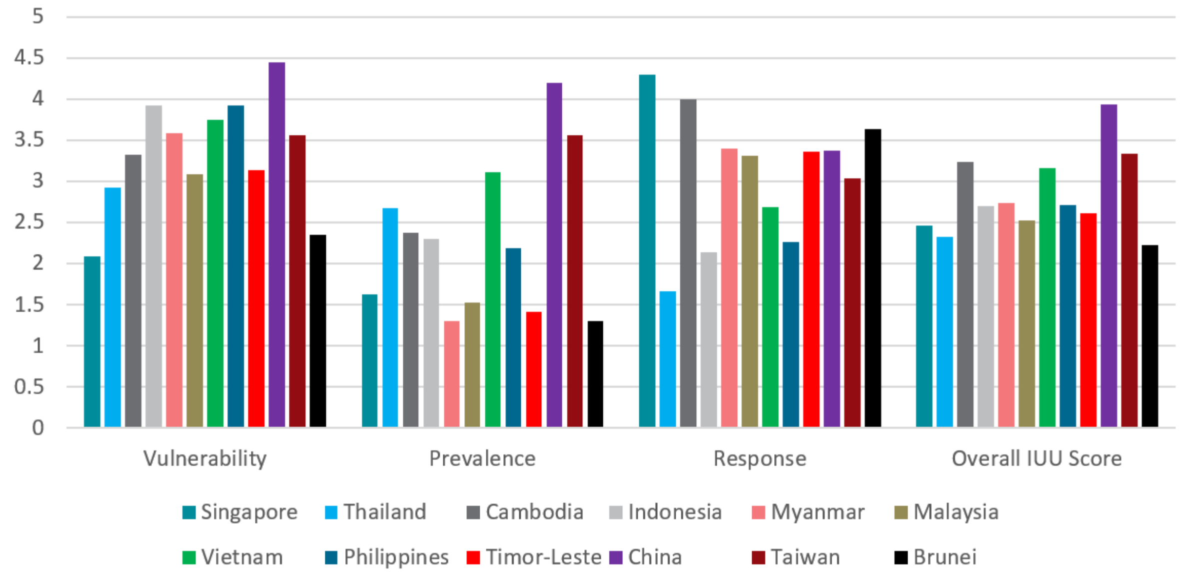
Source: IUU Fishing Index, Cebr analysis

A breakdown of the scores for China, Taiwan and ASEAN nations is shown in Figure 10. It can be seen that significant variation exists among the countries. At a global level, China is ranked as the worst performer, Taiwan the second worst, Cambodia the third worst, and Vietnam the fifth worst. Some other key points worth noting are:

- China is the most vulnerable globally to IUU fishing. Indonesia and the Philippines are 6th and 7th most vulnerable, respectively.
- China, Taiwan, Vietnam and Thailand and Cambodia occupy spots 1 through to 4 globally for prevalence of IUU fishing.
- Singapore scores worst globally for response, with Cambodia in second place.
- Cambodia scores worst globally on aggregated ‘Coastal’ measures. Vietnam is in third place, Myanmar is in fourth place, and Taiwan is in fifth place.
- China and Taiwan are worst and second worst globally for ‘Flag’ measures, which may well impact upon the ASEAN territory.

- China also has the weakest performance in 'Port' measures, potentially providing a safe haven for ASEAN ships.

Figure 10: Country-specific breakdown for China, Taiwan and ASEAN nations, based on IUU Fishing Index Indicators



Source: IUU Fishing Index, Cebr analysis

A general conclusion to be drawn from the index measures is that developing countries are likely to be the most vulnerable to IUU fishing. This aligns well with the claim outlined by Agnew et al (2009), suggesting that IUU practices are encouraged and facilitated by less well-governed states. The key link here then is that developing countries suffer from poorer governance and are less likely to possess adequate resources to combat IUU fishing, meaning greater exposure and vulnerability. The Index measures also fit well with the content of the MRAG Asia Pacific paper, given that they conclude that the Western Pacific is the most vulnerable to – and exhibits the highest prevalence of – IUU fishing.

2.8 Port State Measures

Ports play an essential role in the detection of IUU fishing activities and the enforcement of sanctions. This is reflected in the legislation aimed at preventing IUU fishing:

1993: Agreement to Promote Compliance with International Conservation and Management Measures by Fishing Vessels on the High Seas (FAO compliance agreement).

This agreement came into force in 2003. At a high level, it is composed of three commitments:[30]

30 FAO. (1996). 'Agreement to promote compliance with international conservation and management measures by fishing vessels on the high seas'.

i. It is the responsibility of flag states to ensure that vessels flying their flag do not engage in activities that violate conservation and management measures put in place by international organisations such as RFMOs. Furthermore, this responsibility holds independent of whether the flag state is a member of RFMOs or other fisheries organisations.

ii. A flag state must ensure that its vessels do not fish in the high seas without the permission of the flag state.

iii. The granting of authority of a vessel to fish on the high seas is conditional on the flag state being able to monitor and enforce (control) the activities of the vessel.

1995: Agreement for the Implementation of the Provisions of the UNCLOS relating to the Conservation and the Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (UN Fish Stocks Agreement).

This agreement came into force in 2001. It focuses on the application of the component of the 1982 UNCLOS agreement concerning the conservation and management of highly migratory fish stocks and those which within and out of EEZs.

Article 23 of this agreement, 'Measures taken by a Port State', specifically refers to Port State Measures. In particular, it allows for Port States to undertake inspections of vessels that are voluntarily in its Ports. Furthermore, Port States can put in place regulations that deny the landing/transhipment of catches that are considered to have been caught in a way that is counter to the efforts of conservation and management measures in place for the high seas.[31]

2009: Port State Measures Agreement (PSMA)

The United Nations' Sustainable Development Goal 14.4 – set in 2016 – aims to "end overfishing, illegal, unreported and unregulated fishing…" by 2020. Although progress has been made, early on in 2020 we are still some way off from achieving this objective. The FAO's Port State Measures Agreement is among the more promising avenues through which the ultimate goal of ending IUU fishing can be achieved.

The principal purpose of this agreement is to prevent IUU catches from entering the international marketplace via ports, thus deterring IUU activities altogether. The PSMA was approved in Rome in late 2009 at the FAO conference, and entered into force on June 5th 2016. At the time of writing (March 2020), there are 65 countries signed up to the agreement, as well as the European Union. The full list is presented in Table 6.

31 United Nations General Assembly. (1995). 'Agreement for the implementation of the provisions of the United Nations convention of the law of the sea of 10 December 1982 relating to the conservation and management of straddling fish stocks and highly migratory fish'.

Table 6 Signatories to the Port State Measures Agreement

Signatories to the Port State Measures Agreement	
Albania	Mauritania
Australia	Mauritius
Bahamas	Montenegro
Bangladesh	Mozambique
Barbados	Myanmar
Cabo Verde	Namibia
Cambodia	New Zealand
Canada	Norway
Chile	Oman
Costa Rica	Palau
Cuba	Panama
Ivory Coast	Peru
Denmark	Philippines
Djibouti	Republic of Korea
Dominica	Saint Kitts and Nevis
Ecuador	Saint Vincent and the Grenadines
European Union	Sao Tome and Principe
Fiji	Senegal
France	Seychelles
Gabon	Sierra Leone
Gambia	Somalia
Ghana	South Africa
Grenada	Sri Lanka
Guinea	Sudan
Guyana	Thailand
Iceland	Togo
Indonesia	Tonga
Japan	Trinidad and Tobago

Kenya	**Turkey**
Liberia	**United States of America**
Libya	**Uruguay**
Madagascar	**Vanuatu**
Maldives	**Viet Nam**

While it is encouraging that 88 coastal states are now signatories to the PSMA, the absence of China – which has the world's largest fishing fleet – and Russia in the above list represents a highly significant gap in the coverage of the agreement.[32] Indeed, Russia has two of the world's three busiest ports in terms of the volume of commercial fish landed, while China has four of the twenty busiest ports. Other notable absentees to the list of signatories are Iran, Kiribati, Malaysia, Morocco, Papua New Guinea, and Pakistan – all of which are home to ports ranked among the 50 busiest in the world in terms of commercial fish landings. This means that 23 of the world's 50 busiest ports are located in countries that are not party to the PSMA.[33]

The agreement is applied by port states for vessels that do not fly the flag of the state, both prior to entry of a port and when in the port. Table 7 provides a summary of some of the key measures in the PSMA.

Table 7: The Port State Measures Agreement

Measure	Article No.	Discussion
Port designation	Article 7	Vessels may be restricted to only use certain ports. Article 7 of the PSMA stipulates that relevant parties must make clear which ports foreign vessels may request the entry for.
Advance notification	Article 8	Vessels must provide notification to ports prior to entry.
Documentation & Entry	Article 8,9	The PSMA states the minimum information requirements that port states must request, which include: vessel purpose, vessel name, vessel type, vessel dimensions, flag state, owner, contact information, ID, RFMO ID, and whether the vessel is fitted with VMS. Based on this information, the port may view that a given vessel has engaged in IUU activities and in turn decide to deny entry to the vessel. If the vessel is denied, Article 9 of the PSMA stipulates that the port state informs the denied

32 https://www.maritime-executive.com/editorials/china-is-key-to-closing-ports-to-illegally-caught-fish

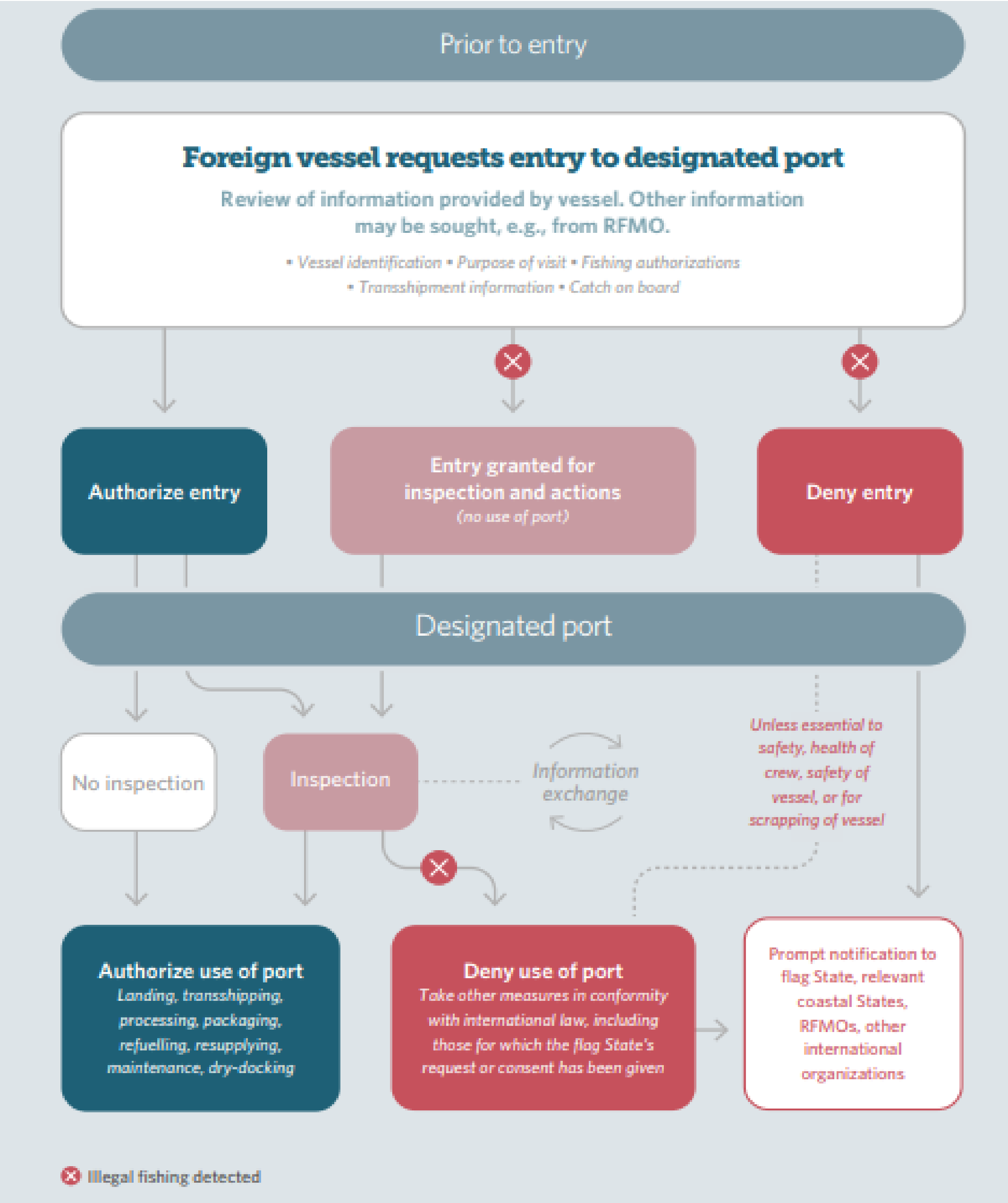
33 https://www.pewtrusts.org/en/research-and-analysis/articles/2016/01/05/new-analysis-identifies-worlds-largest-and-busiest-fishing-ports

		vessel's flag state of their decision (and possibly other coastal states and RFMOs).
Service restrictions	Article 9	Vessels may be restricted in the services and supplies they receive from ports.
Treatment of vessels against which there exists evidence of IUU fishing	Article 9	Vessels that have been found to engage in IUU activities will be denied use of ports or certain port services.
Information sharing	Article 6, 15,16	The PSMA requires that parties share information with other relevant states and organisations such as the FAO and RFMOs. This therefore involves cooperation at regional, sub regional and global levels. Inspection results should be shared with the flag state of the inspected vessel and, where appropriate, the states within whose waters there is evidence that IUU fishing occurred, the relevant RFMOs and the FAO/other relevant international organisations. To facilitate information sharing, parties should establish a communication mechanism allowing direct electronic data exchange.
Inspections	Article 12	Ports may be required to make a minimum number of inspections. Article 12 of the PSMA stipulates that this minimum number should be agreed through relevant parties, while the specific vessels to inspect may be based on information – potentially from other states – that indicates these vessels may be engaging in IUU activities.

Source: FAO (2016), Cebr analysis

The crucial takeaway is that the right to peaceful passage referenced above does not apply to ports where states still maintain sovereignty over access. Therefore, permission to dock can be denied if IUU fishing is suspected, blocking the illegal catch from entering the market. This process is set out in Figure 11.

Figure 11 Enactment of PSMA



Source: The Pew Charitable Trusts and the FAO (Matthew Camilleri)

A potential weakness of the PSMA is the reliance on ports independently enforcing the standards. Ports benefit from remaining competitive through the revenues that come with incoming traffic.[34] This can create an incentive against unilaterally upholding high standards, if this leads to reduced vessel traffic. On the other hand, if seafood buyers and other industry partners begin to exhibit a preference towards ports seen to be implementing the PSMA effectively, this would accelerate the adoption of the port state measures.

34 Molenaar, Erik Jaap. (2006). [‘Port State Jurisdiction: Toward Comprehensive, Mandatory and Global Coverage.’]

3. Agent-based model of IUU fishing

The insights presented in this report regarding IUU fishing and the impacts of information sharing are derived from an agent-based model that simulates a population of fishing vessels and enforcement agents operating across two distinct jurisdictions. Some characteristics of this model are inherited from the model developed in an earlier phase of this research, which focussed on the impacts of various enforcement parameters on the prevalence of illegal fishing in a generalised ocean environment. The various features of this original model are presented in Section 3.1, while Section 3.2 details the ways in which the model has been expanded to facilitate the analysis described in this report.

3.1 Original model

The original model contained three classes of agent: fish, fishing vessels, and enforcers. These agents operated in a square grid that represented the ocean. The grid's constituent patches were also populated with a dynamic stock of plankton, that acted as a source of nutrition for the fish. The behaviours of each type of agent are described briefly below:

- **Fish:** new fish were added to the environment when members of the existing fish population reproduced, while fish were removed from the model either when they were captured by a fishing vessel agent or when they could not obtain sufficient nutrition (through the consumption of plankton). Fish movement was designed to emulate the schooling activity observed in many fish populations.

- **Fishing vessels:** fishing vessels moved around the environment with the goal of catching fish. The vessels were able to choose between fishing illegally (by conducting IUU activities) or legally. The incentive for IUU fishing was a lower marginal cost (reflecting the use of prohibited equipment or illegal processes), while the disincentive was the risk of being detected by an enforcement agent and fined. Fishing vessels' sole objective was to maximise profits. This meant that they would always select the course of action associated with the highest expected profits, irrespective of whether this involves acting legally or illegally. It was assumed that any fish caught were instantaneously sold at the prevailing market price, increasing the level of the fishing vessel's wealth. Meanwhile, fishing vessels' wealth was depleted by the costs associated with catching fish, remaining in the ocean, and any fines that were imposed for IUU activities. Fishing vessels departed the market when their wealth fell below zero.

- **Enforcement agents:** enforcement agents patrolled the model environment, scanning their surroundings for fishing vessels that were acting illegally. The area that each enforcement agent could monitor at any given time was based on a parameter reflecting the radius of their vision. This parameter was designed to capture the effectiveness of enforcement agents and / or the technologies deployed. The assumption was that all fishing vessels detected as conducting IUU activities were automatically fined an amount proportional to the size of their catch.

The key parameters of interest in the previous research were:

- The size of the fine, which was modelled as proportional to the value of the guilty fishing vessel's catch;

- The enforcement agents' radius of vision, which determined the likelihood of IUU fishing acts being detected, and;

- The incentive for illegal fishing activities, which was determined by the ratio of the marginal costs incurred by fishing legally and illegally.

It is important to note that the ABM was a simplified and generalised model of a fishery system, and the quantitative outcomes of the modelling should not be treated literally or as specific predictions of the effects of policy interventions.

A range of scenarios were modelled, including:

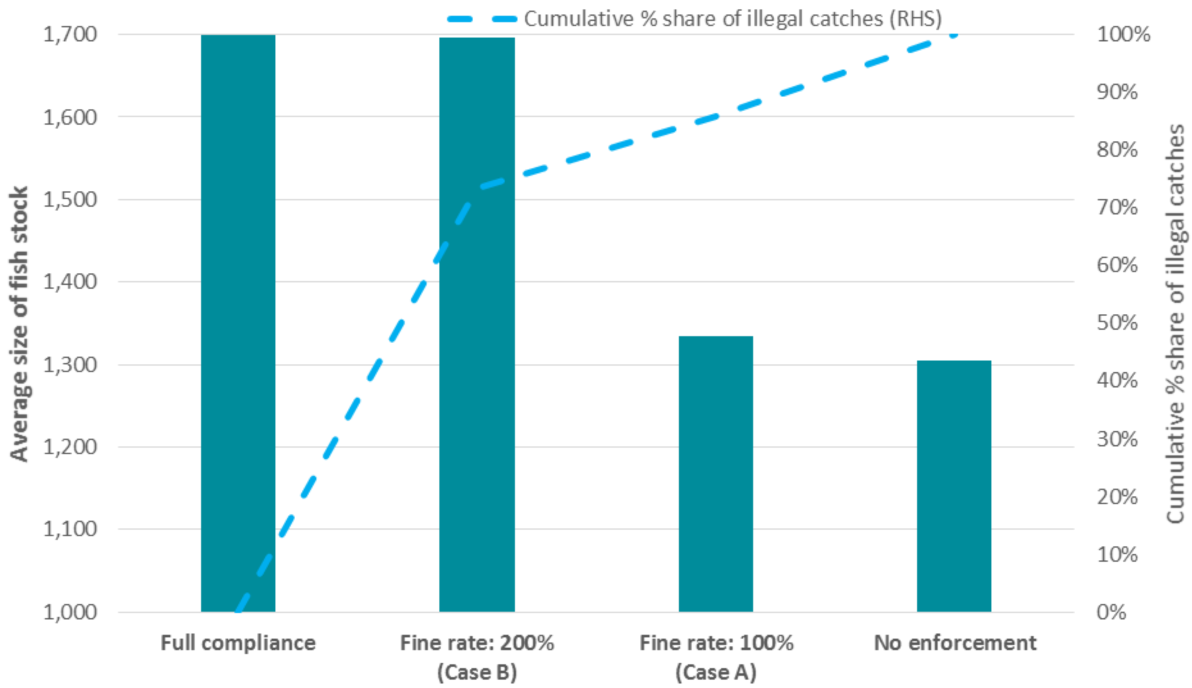
- **Full compliance case**, where there was no difference between the legal and illegal cost functions, eliminating the incentive to conduct IUU activities;

- **No compliance case**, where there were no mechanisms in place to detect and / or punish fishing vessels that operated illegally. Since fishing vessels were pure profit maximisers in the model, this meant that all fishing actions were carried out illegally since the costs associated with doing so were lower while the probability of detection was zero;

- **Intermediate cases**, which had varying levels of fine rate and enforcement agent vision.

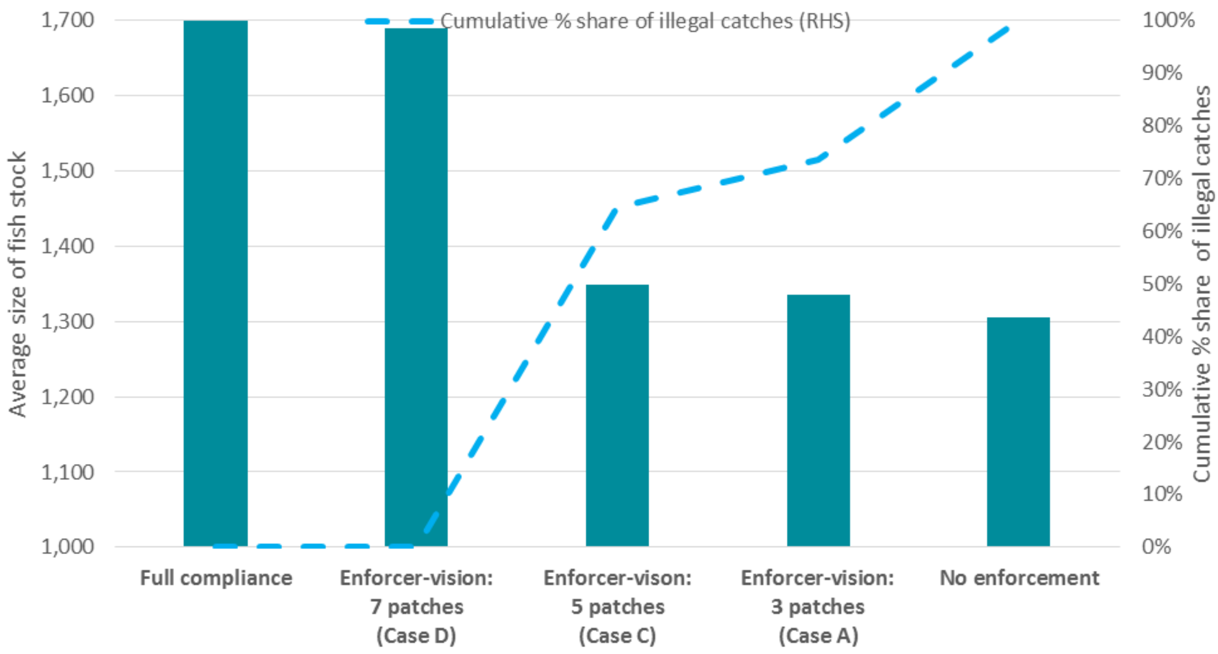
The first set of intermediate cases focussed on the impact of adjusting the fine rate. The average size of the fish stock was found to increase significantly between the extreme scenarios of full compliance (when the fish stock size averaged approximately 1,700) and no enforcement (when the fish stock size hovered around 1,300). In the case of a 100% fine rate (such that fishing vessels that were identified as having conducted IUU activities would be fined a sum equal to the size of their profits that period), the average size of the fish stock rose slightly as some fishing vessels were induced to operate legally. This came about because of the quadratic nature of the cost function, which meant that the profit-maximising catch was lower for legal activities than it was for illegal activities. This in turn meant that average catches tended to be higher when more fishing vessels were operating illegally, which weighed on the average size of the fish stock. Increasing the fine rate to double the fishing vessel's period profits had the effect of raising the fish stock towards the level observed in the full compliance scenario, although rates of illegal fishing remained high.

Figure 12 Modelling results with varying levels of fine rate



The next set of intermediate cases looking instead at the effects of adjusting enforcement agents' radius of vision. There were small but steady increases in the average size of the fish stock when moving from the scenario of no enforcement to scenarios where enforcement agents had a radius of vision of 3 patches and 5 patches. The cumulative share of illegal catches also declined from 100% in the scenario with no enforcement to around 65% in the scenario where enforcement agents had a radius of vision of 5 patches. There was a threshold value of enforcement agents' vision beyond which fishing vessels' actions changed markedly. Indeed, increasing the radius of enforcement agents' vision to 7 patches eliminated all IUU fishing activities, by raising the probability of detection to a sufficient degree. The average size of the fish stock also converged towards the level in the full compliance scenario.

Figure 13 Modelling results with varying levels of enforcement agent vision



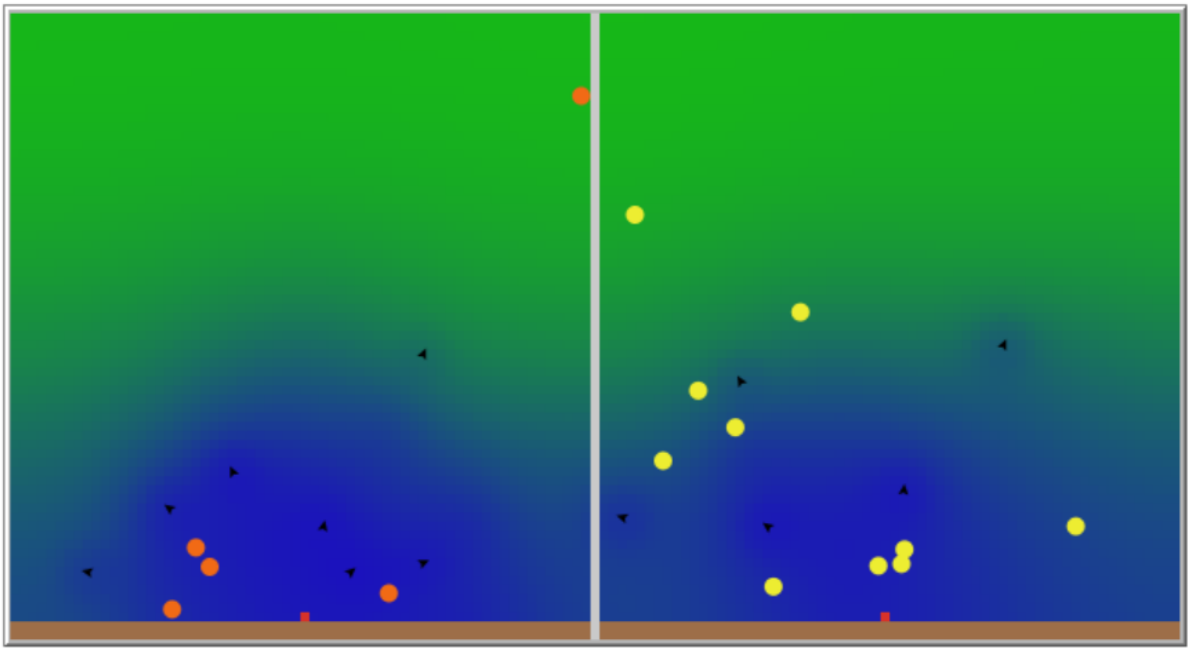
The results of the modelling summarised above demonstrated clearly the significant impact that regulatory policy levers can have on the incidence of IUU fishing and on the health of the biological system. A key finding was the high effectiveness of expanding enforcement agents' vision as a tool for deterring IUU fishing. It was also interesting to observe the presence of an apparent threshold level of enforcement agent vision, beyond which dramatic improvements in outcomes could start to be realised. While increasing the fine rate was found to be an effective policy lever to an extent, there are practical limitations associated with lifting the fine rate. For instance, many fishing vessels cannot afford to pay the fines after a certain level, while there is also a high social cost associated with this policy if there is a risk of false detections.

3.2 Model extensions

The objective of the most recent tranche of modelling is to examine the impacts of information sharing between enforcement agents and ports in different jurisdictions – a concept that lies at the heart of the FAO's Port State Measures Agreement. This requires several key updates to the agent-based model, most notably the introduction of ports and the division of the model environment into two distinct jurisdictions, each with their own independent regulatory framework. In addition to these updates, there have been several other important changes in the modelling of the biological system and the behaviours and preferences of the fishing vessel agents.

Figure 14 is an image taken from NetLogo that illustrates the final form of the updated agent-based model. The circular objects represent enforcement agents (orange circles are enforcement agents from country A and yellow circles are enforcement agents from country B). The black triangular objects denote each fishing vessel agent, and the red squares at the bottom of the figure denote each country's respective port. The colour of the background patches is determined by the level of biomass in each patch during each period, with blue patches representing areas where biomass is heavily depleted and green patches representing areas with a high level of biomass. Finally, the grey line running through the centre of the model is the sea border between country A and country B.

Figure 14 Illustration of agent-based model



The remainder of this section discusses in detail each of the key adjustments that have been made to the model.

Biomass framework

Following consultation with The Pew Charitable Trusts and the Oxford Martin School it was determined that the agent-based model could be made more parsimonious by no longer modelling the fish as individual agents, replacing these with a biomass parameter representing a fish population.

Within the new biomass framework, each patch in the model environment is attributed with a biomass variable, which is initially assigned a random value between 0 and the carrying capacity of the patch. The carrying capacity is assumed to be the same for all patches in the model environment. The biomass variable is sufficiently general so as to encapsulate a range of concepts, such as the tonnage of fish or the population of fish in a specific part of the ocean.

After the initial level of biomass is assigned throughout the model environment, the level of biomass in each patch then adjusts each period based on the following:

a) **Biomass growth rate:** the level of biomass evolves based on a logistic growth function, which is driven by the biomass growth rate and the patches' carrying capacity. The carrying capacity reflects the maximum sustainable long run level of biomass for a certain patch.

Equation 1 below describes the logistic growth function for the change in the level of biomass for patch “i” at time “t”:[35] [36]

$$\Delta\ Biomass_{i,t} = r_{biomass_i} \times \left(1 - \frac{Biomass_{i,\ t-1}}{Carrying\ capacity_i}\right) \times Biomass_{i,\ t-1}$$

Equation 2 Logistic growth function for patches' biomass variable

b) **Movement of biomass across the environment:** this is modelled by a diffusion of biomass between patches each period, allowing for a general movement of fish from areas of high concentration to areas of low concentration. The level of fish movement that takes place within the model environment is highly dependent on the species being considered. For instance, for migratory species such as tuna, it would be appropriate for the biomass to exhibit a high degree of movement within the model environment, whereas for other species the level of movement would be close to zero. The core purpose of the modelling throughout this research has been to uncover regulatory principles, incentives, and enforcement mechanisms that can most effectively be deployed to manage the issue of IUU fishing. To preserve the generality of these findings, the ABM seeks to avoid focussing on specific fish species or geographical areas. With that being said, the diffusion parameter could in theory be adjusted to facilitate high-level insights into how the broad characteristics of the local fish population impact the model’s results. In the scenarios analysed in this report, it is assumed that the biomass travels at a rate of one patch per period.

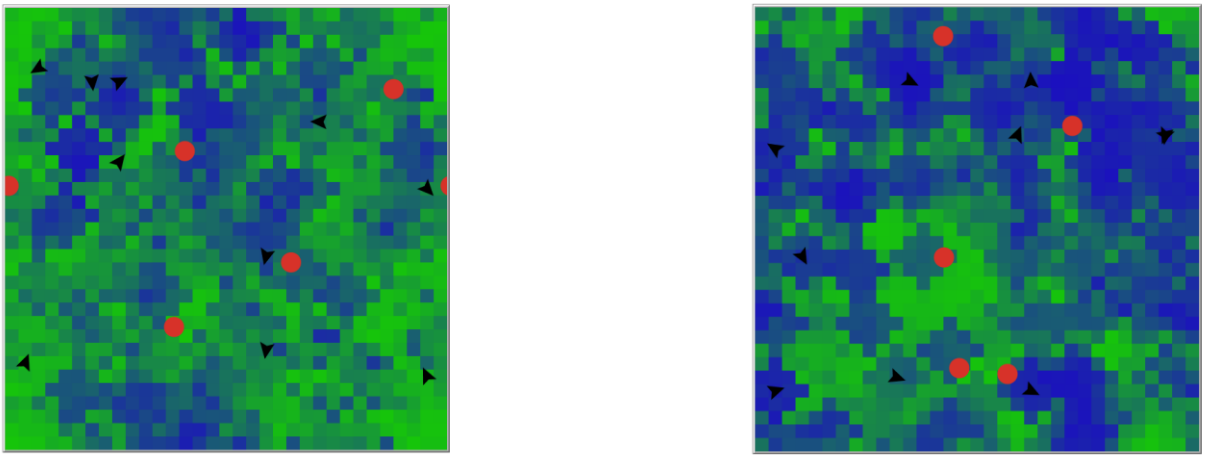
c) **Level of fishing in each patch:** each period, fishing vessels either in or in the proximity of a patch may opt to deplete a certain amount of that patch’s biomass, depending on the expected profitability of any fishing actions.

Figure 15 below illustrates the biomass framework being run within NetLogo, with the red circles representing enforcement agents and the black arrows representing fishing vessels. Green areas of the model environment correspond to patches with a high level of biomass, and blue areas correspond to patches with a low level of biomass – usually a result of a high intensity of fishing in the preceding periods.

35 $r_{biomass}$ denotes the intrinsic growth rate of the biomass.

36 The new biomass framework that is in place would allow for the carrying capacity and biomass growth coefficient to vary across different patches. This would allow for the representation of specific areas of ocean that have intrinsic characteristics which allow them to sustain larger or faster growing fish populations. The carrying capacity and biomass growth rates could also be adjusted to reflect different fish species.

Figure 15 Visual illustration of biomass framework in NetLogo



The transition from the plankton-consuming fish framework to the biomass patch framework involves a significant logistical shift. In the previous framework, impact of fishing vessels' collective activities on the fish population could be deconstructed into a series of binary outcomes: each period fish agents would either be caught by a fishing vessel and removed from the population or they would not be caught and remain in the population (provided other survival conditions are satisfied). In the biomass patch framework, there is a more continuous process, whereby fishing activities lead to a decrease in the value of the biomass variable in certain patches.

The depletion of biomass by fishing vessels takes place in the following way:

1. Each period, fishing vessels assess the level of biomass that is within their catchable range. In order to facilitate a more sustainable system – and to reflect more accurately the conditions faced by fishing vessels – it is assumed that each vessel is only capable of catching a pre-specified share of the biomass within its catchable range. For instance, if there are 1,000 units of biomass in the area within a fishing vessel's catchable range, and fishing vessels can catch 10% of the available biomass each period, the vessel will be able to extract a maximum of 100 units of biomass that period.

2. The fishing vessel will then deplete the desired quantity of biomass (subject to the above constraint) from the patches within its catchable range. The quantity of extraction from each patch within the catchable range is proportional to the level of biomass that each patch has, such that patches with a higher level of biomass will have commensurately more biomass extracted than patches with lower levels of biomass.

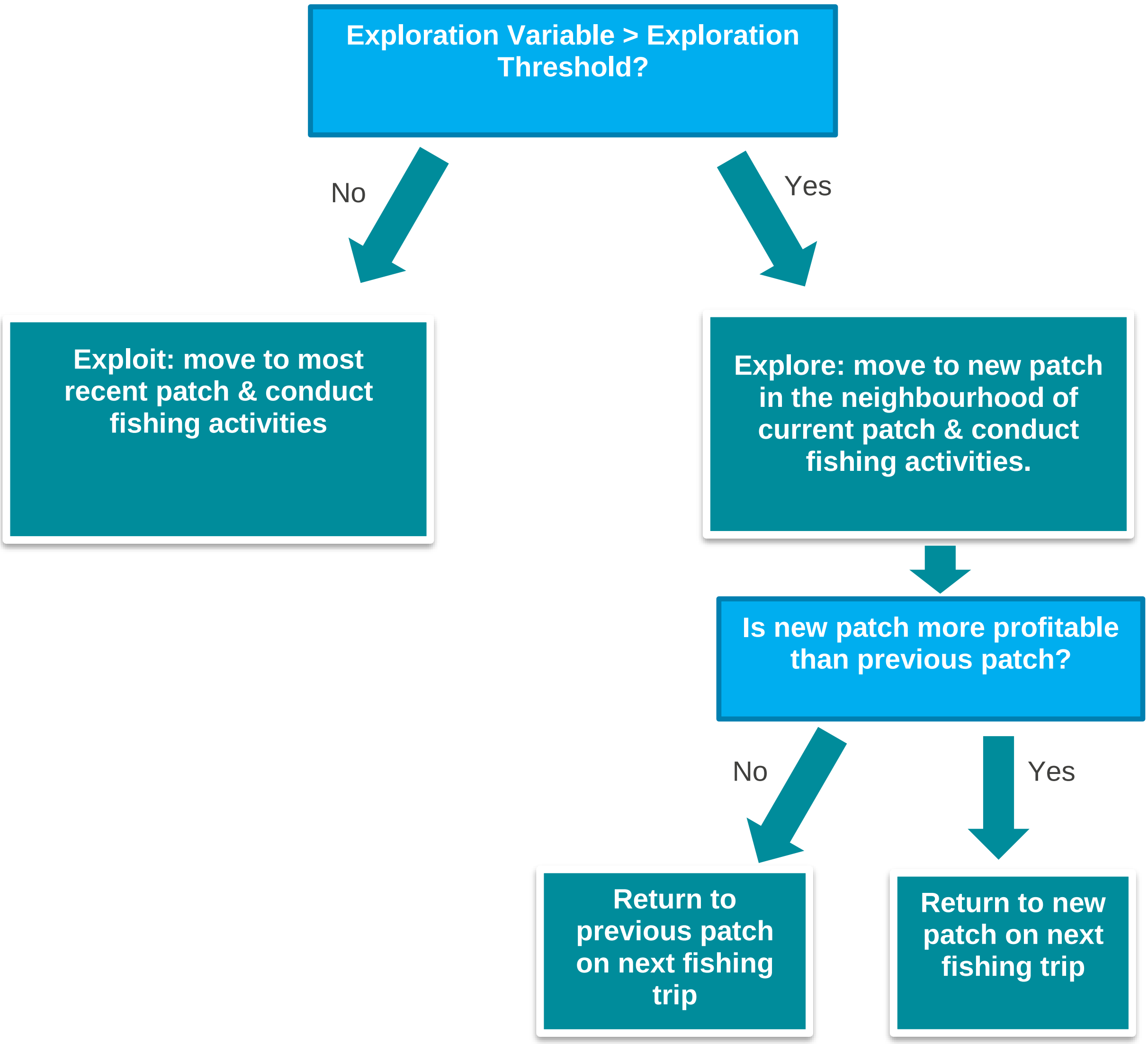
Explore-exploit movement pattern

Another foundational adjustment to the ABM is the adoption of an explore-exploit framework to model the movement of fishing vessels around the environment. Within this framework, before departing from port, each fishing vessel randomly chooses whether to explore (move to a new patch) or exploit (return to the patch of the previous fishing trip). This approach has been based on past modelling carried out by the Oxford Martin School.[37]

The likelihood of a vessel choosing to explore each period is determined by the value of the "exploration threshold" parameter. Each time a fishing vessel must make the decision of whether to explore or exploit, a random number is generated for the vessel, referred to forthwith as the "exploration variable". If this number exceeds the "exploration threshold", the vessel will choose to explore. Otherwise, it will return to the location of its most recent fishing trip. If a fishing vessel does explore, and the new patch proves less profitable than the previous patch, the fishing vessel by default will return to the previous patch in the following fishing trip.

The explore-exploit decision making process is summarised in Figure 16 below:

Figure 16 Explore-exploit decision making process



37 Bailey, R.M., Carrella, E., Axtell, R. et al. A computational approach to managing coupled human–environmental systems: the POSEIDON model of ocean fisheries. Sustain Sci 14, 259–275 (2019). https://doi.org/10.1007/s11625-018-0579-9

IUU aversion

Once fishing vessels have decided upon and arrived at the patch where they will conduct their fishing operations, they must then decide each period whether to operate legally or illegally. An assumption made in original ABM was that fishing vessels' decisions on whether to fish legally or illegally were governed solely by the profits and expected profits associated with each course of action. These in turn were determined by variables such as the fine rate, the detection probability and differing the cost functions associated with legal and IUU fishing. This is consistent with the neo-classical theory of the firm, which states that businesses will make decisions in order to maximise their profits. However, under certain modelling scenarios – for instance where the probability of detection is negligible, or the costs of illegal fishing are significantly lower – this assumption led to outcomes in which all fishing activities were conducted illegally. While studies have shown that the share of IUU fishing is likely to be in excess of 30% in certain regions, an outcome in which all vessels carry out all of their activities illegally does not reflect the observable conditions in the vast majority of the world's fisheries.

To promote modelling outcomes that are more credible and aligned with real-world conditions, varying degrees of aversion towards conducting IUU activities have been introduced to fishing vessels' preferences. At the start of a simulation, each fishing vessel is randomly assigned an "IUU-propensity" coefficient ranging from 0 to 0.8.[38] Low values of the IUU-propensity parameter reflect a high level of aversion to IUU activities, and vice versa. This coefficient then augments the expected-profit function associated with illegal fishing, such that the payoff from illegal fishing for vessels with a high aversion to IUU activity is significantly diminished. This introduces a further level of heterogeneity to the model – both in terms of vessel characteristics and behaviours – and means that even in regulatory environments in which the expected profits from IUU fishing far outweigh those from legal fishing, there will remain some vessels that choose to operate within the confines of the law.

The change to the choice function that vessels face is outlined in Equation 3 and Equation 4 below, which show the expected payoff from IUU fishing for the cases with and without the IUU-aversion variable.[39] The detection probability term captures fishing vessels' perceived risks of detection, which are based on the share of fishing vessels that received a fine after conducting IUU activities during a fishing trip. This in turn is driven by the effectiveness of enforcement agents i.e. their radius of vision, levels of information sharing between countries as well as the number of enforcement agents in each country.

$$\begin{aligned} Expected\ Profits_{Illegal} \\ &= \{(1 - detection\ probability \mid_{number\ of\ illegal\ acts\ carried\ out\ on\ trip}) \\ &\times (Illegal\ profits \mid_{no\ detection})\} \\ &+ \{(detection\ probability \mid_{number\ of\ illegal\ acts\ carried\ out\ on\ trip}) \\ &\times (Illegal\ profits \mid_{detection})\} \end{aligned}$$

Equation 3 Expected payoff from illegal fishing without criminality coefficient

38 The IUU-propensity parameter was capped at 0.8 in order to prohibit modelling outcomes in which the vast majority of fishing activities are IUU activities.

39 Equation 3 and Equation 4 illustrate how fishing vessel's choice function is affected by the IUU propensity coefficient. The inclusion of ports to the model introduces further complexity to this choice function, as outlined in Equations 5 – 9.

$$
\begin{aligned}
Expected\ Profits_{Illegal} \\
&= IUU\ propensity\ coefficient \\
&\times [\{(1 - detection\ probability) \times (Illegal\ profits\ |_{\ no\ detection})\} \\
&+ \{(detection\ probability)\ \times (Illegal\ profits\ |_{\ detection})\}]
\end{aligned}
$$

Equation 4 Expected payoff from illegal fishing with IUU-aversion coefficient

The IUU-propensity coefficient can be thought to reflect the array of factors that cause economic agents to choose differing courses of action, despite facing the same incentives, regulatory environment and constraints. These factors could include innate characteristics as well as historic behaviours, capturing the idea that fishing vessels that have acted illegally in the past may be less resistant to doing so in the future given their familiarity with these actions.

Another key element that drives illegal activity is economic necessity. The fact that the prevalence of IUU fishing is typically higher in less wealthy regions is likely due to a combination of weaker regulatory systems as well as higher levels of economic hardship, which makes it more likely for fishing vessels to increase their profits through illegal activities when the opportunity exists to do so. To capture this dynamic, the IUU-propensity coefficient variable has been designed such that when a fishing vessel's wealth falls below a threshold level, further declines in the wealth level increase the propensity to commit an illegal act i.e. the aversion to conducting IUU activities is diminished. Specifically, as wealth depletes below this threshold level, an additive term is applied to the vessels' IUU-aversion coefficient, which increases in size as wealth approaches zero.[40] This augmentation of the IUU-propensity parameter is designed to capture the change in fishing vessels' preferences that takes place during periods in which they are more financially strained.

Introduction of ports

The necessity of ports – facilities where boats can dock in order to load and discharge cargo and / or passengers – is one of the key features that distinguishes marine-based economic activities from land-based industries. While the practical challenges associated with monitoring large swathes of ocean make the enforcement of regulations more difficult, the intrinsic need for most vessels to pass through ports creates a natural pinch point at which checks can be conducted and – where applicable – enforcement can be carried out. In most primary industries, each producers' output can enter the market via a multitude of unique paths, involving a range of potential transport networks, wholesalers and supply chains. By contrast, the route to market for ocean-caught fish has a common element for all producers, in the form of ports.

The agent-based model has been expanded in this phase of the research to include ports, in order to capture this uniquely critical component of the regulatory enforcement process for the fishing industry. Ports have been introduced to the model by creating a common geographical location (patch) in the model environment from which the fishing vessels originate. This differs from the original structure of the model where fishing vessels were generated at random locations throughout the environment. To emulate the ways in which boats interact with ports, the following constraint has been added to the fishing vessels' choices and actions:

40 The additive term is capped such that the overall IUU-propensity coefficient for any fishing vessel does not exceed 1 (which would imply a preference for fishing illegally rather than legally even if there is not an economic incentive to do so).

- Fishing vessels must return to the specified port location once either of the following two criteria are met:

    1. The amount of fish they have caught during the fishing trip reaches the vessel's maximum capacity, or;

    2. The amount of time that the fishing vessel has spent at sea exceeds the maximum number of consecutive periods that they are able to spend at sea. This reflects a variety of practical considerations such as the need to re-fuel, rotate crew personnel and ensure that any catch does not become spoiled.[41]

The introduction of ports fundamentally changes the way in which fishing activities are spatially distributed across the modelled environment, and also adds an important element to the fishing vessels' strategic choice process. In the previous framework, fishing vessels' movements around the environment were not forward looking, with boats choosing where to fish on the basis of the catch that was currently visible to them from their current location. In the extended model, the selected fishing location is based on a more comprehensive strategic plan outlining a fishing vessel's activities for an entire fishing trip spanning multiple periods, factoring in the past profitability of certain patches as well as the time and travel costs associated with reaching them. These considerations are summarised in Table 8 below:

Table 8 Factors feeding into fishing vessels' decisions on where to fish

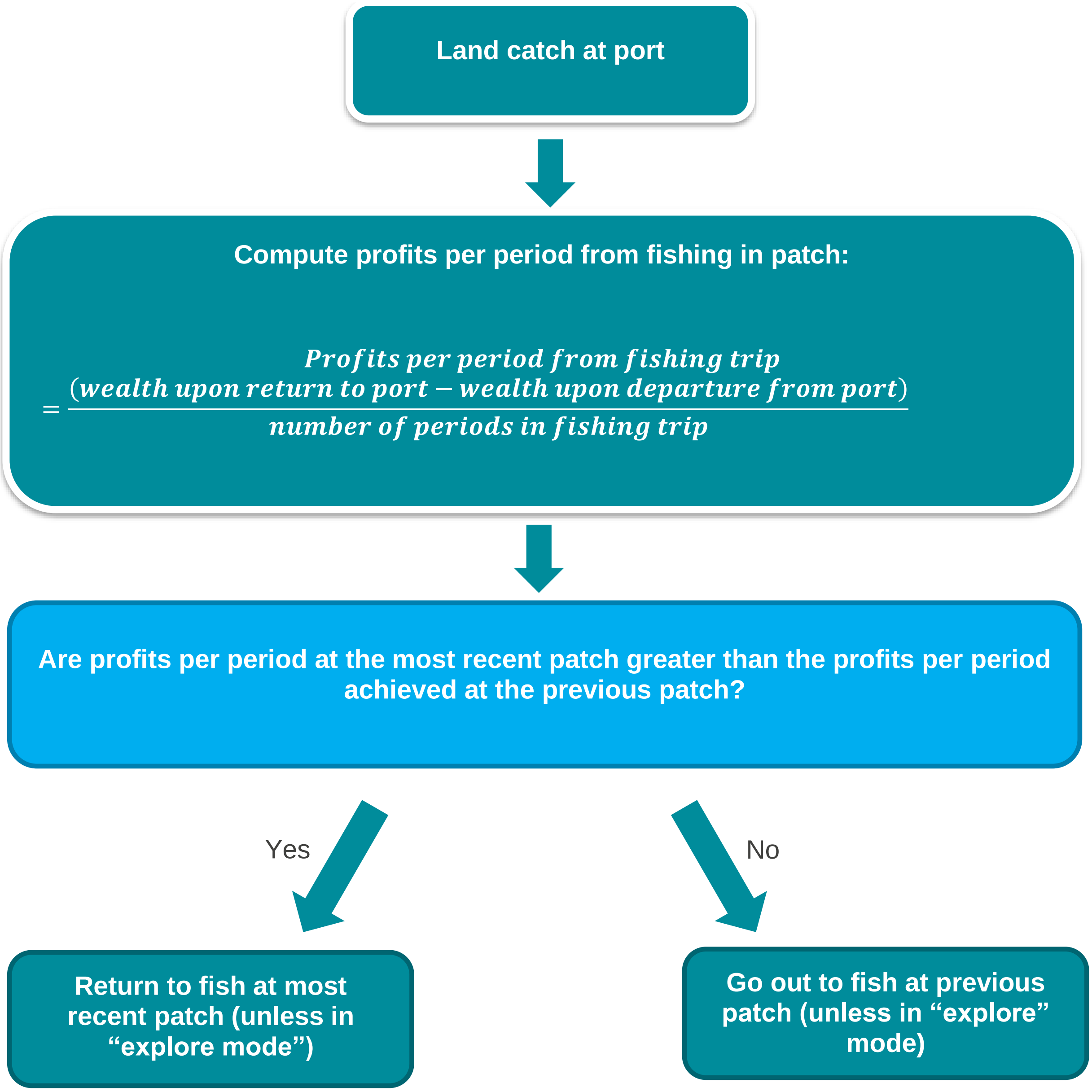
Original agent-based model	Extended agent-based model
If there are fish within the vessel's catchable range, the vessel will remain where it is and catch the desired quantity of fish. Otherwise, it will scan its current surroundings to establish whether there are fish within the visible radius. If so, it will move in the direction of these fish. If not, the vessel will move forward in the direction it is currently facing.	Opportunity cost associated with travelling to patches – each unit of time that is spent moving towards a certain patch comes at the expense of the catch that could be attained by fishing during that period rather than travelling.
	Fuel cost associated with travelling to patches – fuel costs increase proportionately with the distance travelled.
	Comparison of profitability of most recent patch with the profits achieved at the previous patch.

Figure 17 illustrates the sequence of computations that take place when the fishing vessels return to port in order to land their catch. Note that each fishing trip comprises several

41 The presence of transhipment operations can change this dynamic by allowing fishing vessels to offload their catch aboard a separate vessel without returning to port.

periods (during which fishing vessels are either travelling towards a particular patch or carrying out fishing activities).

Figure 17 Sequence of decisions upon return to port



An important change that effects fishing vessels’ decision-making process each period is that each fishing trip now comprises multiple periods, during which vessels can choose to operate either legally or illegally. Fishing vessels that are detected conducting IUU activities at any point during a fishing trip are fined an amount proportional to their entire catch from that trip, including any catch that was caught legally. Note also that at any point in time, fishing vessels are unaware of whether any prior illegal activity conducted during the fishing trip was detected by enforcement agents. Therefore, each decision to operate illegally increases the probability of being detected at least once during the fishing trip, and thus increases the risk of a fine being imposed at a level proportional to the fishing vessel's entire catch.

To summarise, when a fishing vessel decides whether to operate legally or illegally, it must now consider:

1. The likelihood that it has been detected conducting IUU activities during a prior period of the fishing trip, ρ_{prior}:

$$\rho_{prior}|_{number\ of\ illegal\ acts\ carried\ out\ on\ trip} = 1 - (1 - \ detection\ probability\ per\ period)^{number\ of\ illegal\ acts\ carried\ out\ on\ trip}$$

Equation 5 Probability of prior detection

2. The risk of being detected acting illegally at some point during the fishing trip, conditional upon acting illegally in the current period, $\rho_{detection\ current}$:

$$\rho_{current}|_{number\ of\ illegal\ acts\ carried\ out\ on\ trip\ and\ decision\ to\ conduct\ IUU\ activity\ in\ current\ period} = 1 - (1 - \ detection\ probability\ per\ period)^{number\ of\ illegal\ acts\ carried\ out\ on\ trip+1}$$

Equation 6 Probability of being detected at least once on the fishing trip if IUU activity is conducted in the current period

3. The increased risk of being detected at least once during the entirety of the fishing trip as a result of acting illegally in the latest period, $\Delta\rho$, and the impact on profits of the associated fine imposed on the entirety of the fishing vessel's prior catch:

$$\Delta\rho = \rho_{current} - \rho_{prior}$$

Equation 7 Change in detection probability over entire fishing trip as a result of IUU activity conducted in current period

The new dynamics mean that the profitability of both legal and illegal fishing activities is subject to uncertainty. This is because, even if a fishing vessel chooses to operate legally in a particular period, there is the possibility that any profits associated with this action are subject to a fine if that vessel has conducted IUU activities during at least one earlier period of the fishing trip.

Equation 8 and Equation 9 present the expected profit function for legal and IUU fishing activities, respectively. In these equations, revenues are denoted by y and costs are denoted by x:

$$Expected\ Marginal\ Profits_{Legal} = \{(1 - \rho_{prior}) \times (y_{upcoming\ period} - x_{upcoming\ period})\} + \{\rho_{prior} \times (y_{upcoming\ period} - x_{upcoming\ period}) \times (1 - Fine\ rate)\}$$

Equation 8 Expected profit function for legal fishing activities

Meanwhile, the expected profits from IUU fishing activities are computed as:

$$\begin{aligned} Expected\ Marginal\ Profits_{Illegal} &= \{(1 - \rho_{current}) \times (y_{upcoming\ period} - x_{upcoming\ period})\} \\ &+ \{\rho_{current} \times (y_{upcoming\ period} - x_{upcoming\ period}) \times (1 - Fine\ rate)\} \\ &- (\Delta\rho \times (Fine\ rate) \times (y_{previous\ periods} - x_{previous\ periods})\} \end{aligned}$$

Equation 9 Expected profit function for IUU fishing activities

The final term Equation 9 captures the increased risk of a fine being imposed on the profits made during earlier periods of the fishing trip as a result of the decision to operate illegally in the current period. The magnitude of this term increases throughout the fishing trip, meaning that the risks associated with IUU fishing are higher at the latter stages of a fishing expedition.

Another consequence of the addition of ports to the agent-based model is that a high share of fishing activity is typically concentrated in patches that are relatively near a port, due to the lower travel and time costs associated with fishing in these locations. Given this change, it is necessary to add a greater degree of strategy to the movement decisions of enforcement agents. To do so, a bias has been introduced into enforcement agents' movements to create a tendency to cluster closer to ports, while preserving a degree of randomness in their movements.

There is a degree of interaction between fishing vessels' choices regarding whether to operate legally or illegally and where they choose to fish during future trips. This is because the decision of whether or not to conduct IUU activities affects the profitability of fishing at a certain patch, which in turn impacts the likelihood that the fishing vessel will return to that patch for future fishing trips.

Development of a two-country environment

The nature of regulatory and enforcement regimes across different jurisdictions vary significantly across the world, with some countries adopting considerably more stringent procedures and structures than others. This regulatory divergence has a significant effect on the incentives that economic agents face, and accordingly shapes their behaviours and decision making. This is particularly true in circumstances where the frictions associated with transacting across borders are relatively limited.

To illustrate the dynamics that can play out in the presence of divergent regulatory structures, consider the following illustrative example:

- Two neighbouring countries (country A and country B), where country A has a loose regulatory structure and country B has a tight regulatory structure. The notion of regulatory structure is a broad concept encompassing a range of policies and procedures, such as:
    - The number of enforcement agents;
    - The effectiveness of enforcement agents in detecting illicit actions;
    - The fines imposed for illicit behaviour, and;
    - The capacity to implement fines or checks.
- Fishing vessels are **not** able to move between country A's waters and country B's waters.

In this scenario, the looser enforcement structure in country A creates a larger incentive for IUU fishing activities in country A's waters, imposing a greater strain on the fish stocks in that country. However, while economic systems are subject to jurisdictional boundaries, the same is not true for biological systems. Over-fishing in country A as a result of lax regulatory procedures will affect the overall health and vitality of the overall aquatic ecosystem that spans across both countries (and beyond). This generates a second order effect of regulatory divergence, whereby looser enforcement structures in one country generate adverse biological outcomes that spill across jurisdictional borders. In economic parlance, one country adopting a looser regulatory framework for the management of its fisheries imposes a negative externality on neighbouring countries, whose aquatic resources are derived from the shared common ecosystem.

Transitioning to a scenario in which fishing vessels are able to move freely between country A's waters and country B's waters adds a further element to fishing vessels' choice function, whereby they must consider which port to return to in order to land their catch. For vessels that have only operated legally throughout a fishing trip, this decision is based solely on the distance to each port and the corresponding fuel costs. This means that it will always be more profitable for fishing vessels that have operated in an exclusively legal manner to return to the port closest to them. Vessels that engage in IUU activity must also consider the probability of being detected and subsequently fined, which varies depending on the chosen port of return. Note that in cases where there is no information sharing between enforcement agents in different countries, the probability of being punished for IUU activities is zero if the illicit actions took place in a separate jurisdiction to that of the selected return port. This dynamic is discussed further below.

Introduction of information sharing between enforcement authorities

The existence of shared biological resources being managed and monitored by distinct regulatory authorities means that co-operation between these authorities has the potential to deliver mutually beneficial outcomes for all parties. This principle lies at the core of the Port State Measures Agreement, discussed in detail in Section 2 of this report.

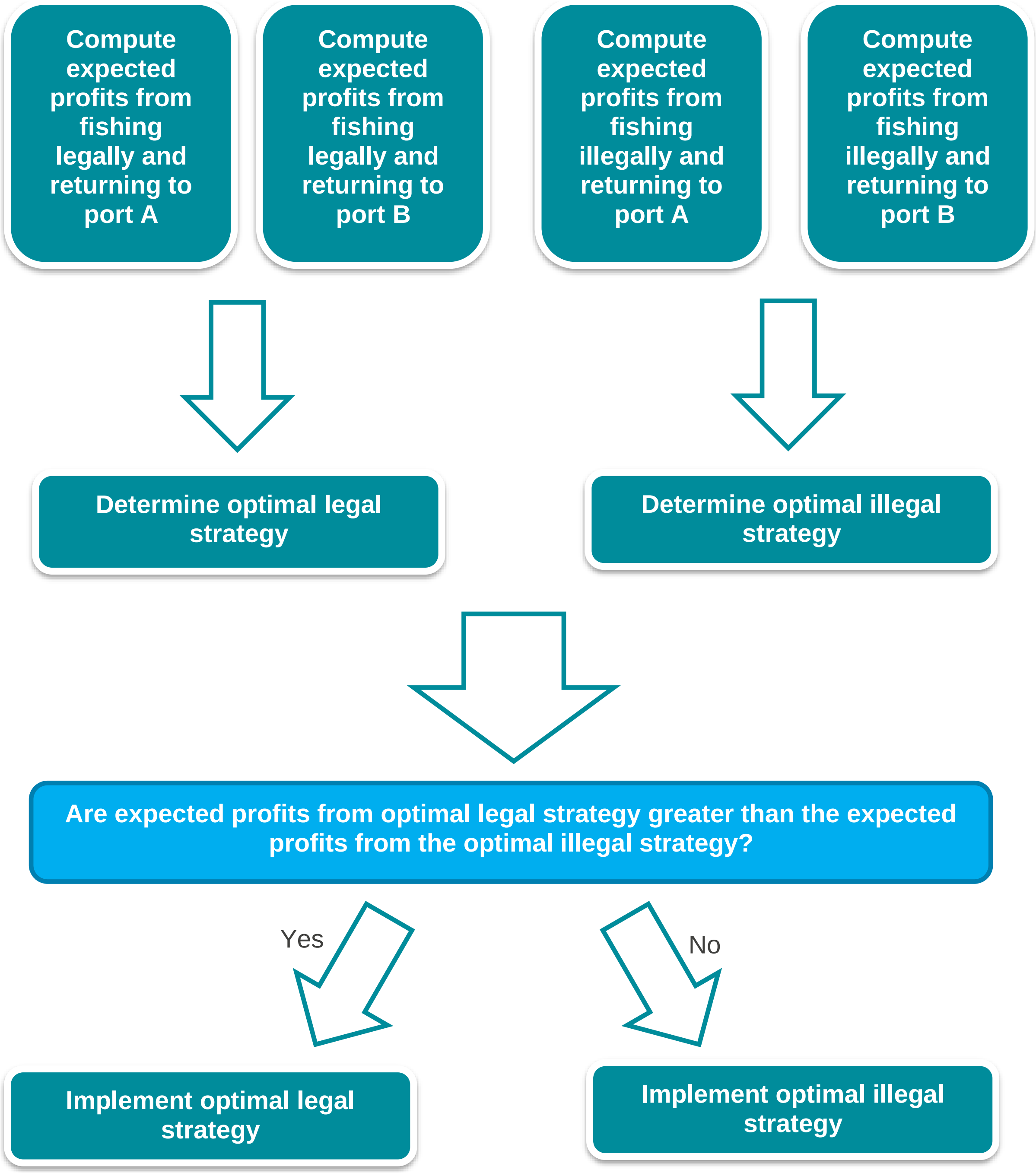
The primary form of information sharing that has been built into the agent-based model involves enforcement agents from one country sharing information with the neighbouring port about specific fishing vessels that they have detected conducting IUU activities. It is assumed that where information is shared between an enforcement agent and a port, the port has received this information by the time the relevant fishing vessel reaches that port. Depending on how this information is processed by the recipient port, the sharing of vessel-specific information enables enforcement to be carried out in either country, irrespective of the landing destination or the geographical location of the illicit acts.

There are, however, practical limitations that must be considered. Most notably, countries with more limited enforcement structures will typically face constraints in the degree to which they are able to process and act upon the information they receive from other countries. For instance, countries with more limited resources may face difficulties carrying out the checks, inspections, data collection and verification, and enforcement procedures necessary for the incoming data on IUU fishing activity to be utilised fully. To account for this, the model also includes a port-capacity parameter, which can be varied depending on the country's ability to act upon incoming information from other regulatory authorities. Capacity constraints capture any obstacles that ports face in imposing sanctions on suspected fishing vessels and are treated as independent to the number of enforcement agents in each country.

The decision on whether to share information is unlikely to be a binary choice on the ground. Even countries that endeavour to maximise co-operation with their neighbours are unlikely to successfully transmit all relevant information to ports in other jurisdictions, since communicational and logistical barriers making a degree of informational leakage likely. To reflect this, the share of IUU actions detected by enforcement agents in one country that are communicated to the port in the other country has been made a variable parameter ranging from 0 to 1, where 0 represents no information sharing and 1 represents perfect information sharing.

The presence of information sharing between enforcement agents in different countries affects the probability of detection at each port, and accordingly influences the expected profitability of the various actions available to fishing vessels during each period. At any point during a fishing trip, fishing vessels determine the optimal port to return to, conditional upon acting legally in the current period, as well as the optimal port to return to conditional upon acting illegally in the current period. The fishing vessels then compare the expected profitability of the optimal strategy for fishing legally with the expected profitability of the optimal strategy for fishing illegally, in order to decide upon a final strategy. This process is illustrated in Figure 18.

Figure 18 Process for deciding whether to conduct legal or illegal fishing activities and which port to return to



Once fishing vessels return to their selected port after a fishing trip, the port checks whether it has information that the fishing vessel has acted illegally, from either its own enforcement agents or - depending on the degree of information sharing - the neighbouring country's enforcement agents. If the port does have information that the fishing vessel acted illegally during its most recent fishing trip, it will impose a penalty with a probability proportional to the capacity of the port.

When making decisions, fishing vessels are faced with imperfect information regarding the risks of detection. To model this, the adaptive expectations framework has been carried forward from the original agent-based model. Within this, fishing vessels each period update their expectations of the probability of being detected conducting IUU activities by analysing the share of past IUU actions (carried out either by themselves or by other fishing vessels) that have been detected, which is now conditional on the country in which the IUU activities are being carried out as well as the chosen return port. While the adaptive expectations assumption is reasonable in the long run, this learning process will take a certain amount of time. To account for this, the model has been refined to include an initial period during which fishing vessels' perceived risks of detection are based on the number of enforcement agents in each jurisdiction and the level of information sharing taking place between the countries, rather than the number of observed detections. This perceived probability gradually converges to the observed probability of detection, modelling the process via which fishing vessels acquire experience and knowledge of their surroundings.

Market exit criteria

In the original agent-based model, fishing vessels would remain active until their level of wealth fell below zero (each period, wealth is depreciated based on the weighted average cost of capital (WACC), which reflects the rate that a firm is expected to pay to its shareholders in exchange for the financing of assets). In the long run, this criterion ensured that fishing vessels exited the market when conditions became economically unprofitable for a sustained period of time. However, it also gave rise to situations where fishing vessels that had previously accumulated high levels of wealth remained in operation for large amounts of time, even when the profits associated with fishing were consistently negative – for instance due to a depleted fish population. Intuitively, it can be expected that fishing vessels will exit the market after they have made losses during successive periods of fishing. To capture this dynamic, a further market exit criterion has been added to fishing vessels' choice function, whereby vessels exit the market if their profits are negative for more than a pre-specified number of periods. The effect of this change is that the structure of the overall fishing market is more responsive to changes to the underlying biological system. In particular, the population of fishing vessels adapts more quickly to changes in biomass levels, adding a natural stabiliser to the system. For instance, after a prolonged period of high extraction, low biomass levels cause increasing numbers of fishing vessels to drop out of the market. This in turn alleviates pressures on the fish population, allowing it to stabilise and eventually grow.

4. Model calibration and scenarios

The objective of the extensions and refinements to the agent-based model described in the preceding section is to explore the impact of information sharing between different countries on the behaviours of participants in the fishing markets and the health of the underlying ecosystems upon which the industry is based.

The key outcome variables of interest are:

1. **Health of fisheries**, as measured by the level of biomass in each country's waters;
2. **Probability of detection,** as measured by the share of fishing vessels that are detected and fined after having carried out IUU activities during a fishing trip;
3. The **revenues generated** by each country through the imposition of fines upon fishing vessels that are found to have operated illegally;
4. **Scale of IUU activity,** as measured by the share of fishing activities that are conducted illegally in each country as well as the share of illegally-caught fish landed at each port, and;
5. **Yield of fisheries**, as measured by the amount of biomass caught by fishing vessels cumulatively as well as during individual periods.

4.1 Scenarios

To examine these impacts, a variety of scenarios have been considered. The various complexities that have been added to the model mean that there is a large number of variables that can potentially be altered. However, in order to extract insights specifically on the theme of information sharing – which is the primary focus of this research – the majority of model parameters have been held constant across the different scenarios. The values of these parameters are presented in Section 4.2. Table 9 presents the scenarios that have been analysed for this research.

Table 9 Description of scenarios analysed

Name	Description	Number of enforcement agents (country A)	Number of enforcement agents (country B)	Information sharing from country A to country B	Information sharing from country B to country A
A	No information sharing, no capacity constraints	10	10	0%	0%
B	Partial & unilateral information sharing from country B to country A, no capacity constraints	10	10	0%	50%
C	Complete & unilateral information sharing from country B to country A, no capacity constraints	10	10	0%	100%
D	Partial & bilateral information sharing, no capacity constraints	10	10	50%	50%
E	Complete & bilateral information sharing, no capacity constraints	10	10	100%	100%
F	No information sharing, no capacity constraints	5	10	0%	0%
G	Partial & unilateral information sharing from high	5	10	0%	50%

	enforcement country to low enforcement country, no capacity constraints				
H	Complete & unilateral information sharing from high enforcement country to low enforcement country, no capacity constraints	5	10	0%	100%
I	Partial & bilateral information sharing, no capacity constraints	5	10	50%	50%
J	Complete & bilateral information sharing, no capacity constraints	5	10	100%	100%
K	Complete & bilateral information sharing, minor capacity constraints in low enforcement country	5	10	100%	100%
L	Complete & bilateral information sharing, major capacity constraints in low	5	10	100%	100%

	enforcement country				
M	Complete & bilateral information sharing, minor capacity constraints in one country	10	10	100%	100%
N	Complete & bilateral information sharing, major capacity constraints in one country	10	10	100%	100%
O	Bespoke scenario 1	10	10	50%	50%
P	Bespoke scenario 2	5	5	25%	50%

4.2 Model calibration

Table 9 outlines the parameters that are systematically varied across the scenarios in order to provide insights into the impact of varying degrees of information sharing under various regulatory contexts. The agent-based model includes numerous other parameters, the values of which have been fixed across each of the scenarios described above. The model calibration is designed to provide a generalised and simplified framework within which to examine the effects of information sharing and other enforcement parameters. As such, the results of the modelling should not be interpreted as predictions for specific fishery systems.

1). Biological parameters

It is important to note that the purpose of the ABM is to uncover generalised patterns of behaviour and outcomes that can result from changes to the regulatory framework. It is not intended as a simulation of specific ecosystems or fisheries. Therefore, while steps have been taken where feasible to ensure that the biological system functions in a way that is representative of real-world fisheries, it has not been designed to emulate any specific fishery. This approach has the advantage of extending the applicability of any findings to a broad range of ecological settings.

The replacement of the plankton-consuming fish agents with the biomass framework has vastly reduced the number of parameters to be calibrated with respect to the biological aspects of the ABM. Indeed, rather than modelling the movement, feeding and reproductive behaviour of individual fish, the biomass framework instead requires parameters of the below logistic growth function to be defined:

$$Biomass_{i,t} = Biomass_{i,t-1} + r_{biomass_i} \times \left(1 - \frac{Biomass_{i,\ t-1}}{Carrying\ capacity_i}\right) \times Biomass_{i,\ t-1}$$

Equation 10 Biomass logistic growth function

Following consultation with the Oxford Martin School – who referred us to the Fishbase.de source – the intrinsic growth rate ($r_{biomass}$) has been set at 0.57. This is the median value of the intrinsic growth rates of a diverse range of pelagic, transboundary fish species, as outlined below:

Table 10 Intrinsic population growth rates of common fish species

Common name	Species	Intrinsic growth rate
Mackerel	Acanthocybium solandri	0.57
Herring	Clupea harengus	0.45
Anchovy	Engraulis ringens	0.83
Cod	Gadus morhua	0.52
Red snapper	Lutjanus gibbus	0.57
Haddock	Melanogrammus aeglefinus	0.5
Pollock	Pollachius pollachius	0.63
Sardine	Sardina pilchardus	0.6

Source: Fishbase.de

Empirical data is highly sparse when it comes to an ecosystem's carrying capacity. While some studies have attempted to estimate the carrying capacity of fisheries at a highly localised level[42], the generality that the ABM seeks to achieve makes it unfeasible to base the value of the carrying capacity parameter on any single ecosystem or fishery. Instead, the value of the carrying capacity has been set at 50. This represents the maximum level of biomass that can be reached in any individual patch. This value was calibrated alongside the parameters governing the amount of fish that vessels can catch each period, in order to produce a system in which biomass levels fluctuate according to the intensity of fishing activity in a manner that would be expected in a representative fishery. The values were set so as to avoid situations where a single fishing vessel could deplete a large portion of a patch's biomass in a short amount of time, as well as the other extreme where high levels of fishing activity did not have an appreciable impact on the level of biomass within each patch.

42 Wroblewski, 2006: A Determination of the Ecosystem Carrying Capacity for Finfish in Gilbert Bay Labrador: A Marine Protected Area

2). Fishing vessel parameters

While the agent-based model's underlying biological framework has been made more parsimonious in this iteration of the research, a high degree of complexity has been added to the fishing vessel agents' behaviours and preferences.

Movement parameters

The timing and direction of fishing vessels' movements around the model environment are determined by the following parameters:

- **Movement rate:** the maximum distance that fishing vessels can travel in a single period is set at **32 patches**. The model environment is a 128 x 64 patch grid (divided equally into country A and country B). Therefore, the distance between the ports and the furthest possible location in the model environment is just over 115 patches. This means that fishing vessels can travel from either port to any location in the environment in four periods or fewer. Note also that fishing vessels are not able to both move and fish during a single period.

- **Time at sea & vessel capacity:** a variety of constraints, ranging from fuel supply and vessel capacity to worker requirements, mean that there is a finite amount of time that fishing vessels can spend at sea before having to return to port. During the model simulations, it is assumed that fishing vessels return to port either when **the amount of biomass extracted during the fishing trip exceeds 200 units** or when **the time spent at sea exceeds 30 periods**.

Cost function parameters

The fishing vessels' cost function during each period of fishing is as follows:

$$Fishing\_cost = Fixed\_cost + (\beta \times x^2)$$

Equation 11 Fishing vessel cost function

Where x is the level of biomass extracted that period and β is the cost coefficient. **For legal fishing actions, the cost coefficient is set to equal 1. For IUU fishing activities, the cost coefficient is set to equal 0.5**, which provides an incentive for some fishing vessels to operate illegally in order to lower their fishing costs. **The fixed cost that is incurred during each period of fishing is set at 10. This element captures those costs that are not proportional to the quantity of fish caught.**

It is important to note that Equation 11 includes only those costs specifically incurred by the act of fishing. Fishing vessels also incur a travel cost that is proportional to the total distance travelled during a fishing trip. This travel cost component influences the overall profitability of fishing at a specific location, which in turn determines the likelihood that a fishing vessel will return to that patch during future fishing trips.

Table 11 Breakdown of costs incurred by fishing vessels

Cost element	Description
Fixed cost	Elements that are not proportional to the quantity of fish caught e.g. repairs, licenses and salaries.
Variable cost	Elements proportional to the quantity of fish caught e.g. equipment, energy / fuel depleted during fishing, bonus / overtime payments to staff.
Travel cost	Cost of fuel from travelling between port and fishing location.

As discussed in Section 3.2, one objective in designing fishing vessels' cost function for legal and IUU fishing activities was to avoid outcomes in which all fishing vessels would choose to operate illegally under the right conditions, since this does not align with the empirical evidence. The parameters for the cost function described above achieve this function.

Fishing capacity

The cost function presented above feeds into the below profit function for fishing activities in a particular period:

$$Profits = (Price\ \times\ x) - Fixed\_cost\ - (\beta\ \times x^2)$$

Equation 12 Fishing vessels' profit function each period

The profit maximising quantity of fish to catch can be derived by differentiating the above profit function with respect to x:

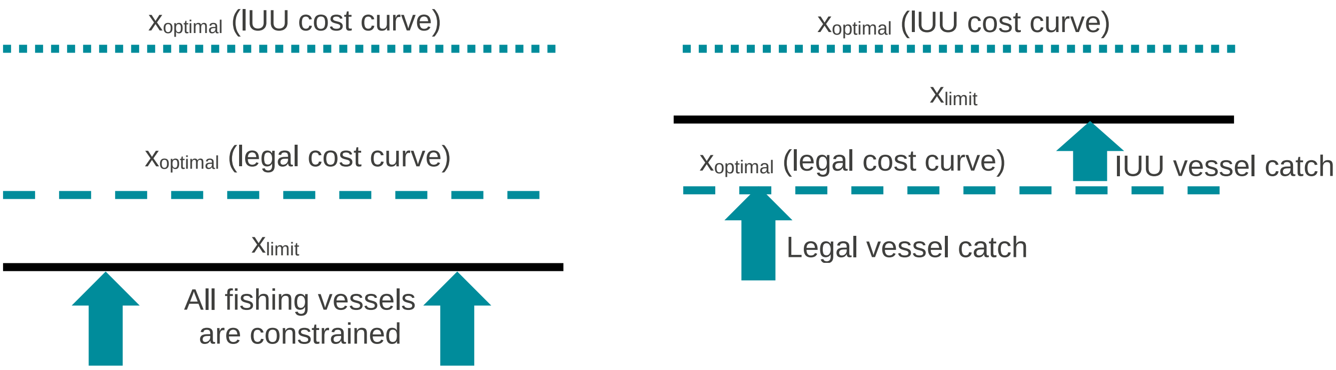
$$x_{optimal} = \frac{Price}{2\ \times\ \beta}$$

Equation 13 Maximisation of fishing vessels' profit function

$x_{optimal}$ is therefore the quantity of fish that fishing vessels would ideally choose to catch each period. However, the quantity of fish that vessels are able to catch each period is determined also by the level of biomass that exists in the patches within each fishing vessel's catchable range. **The catchable range is defined as all patches within a 3-patch radius** of a fishing vessel. The model assumes that **each fishing vessel is able to catch up to 5% of the biomass** that exists within any patch that is within its catchable range during a single period. This essentially imposes a practical ceiling – denoted here on in as x_{limit} – on the quantity of fish that can be caught. This constraint means that in some cases – when the surrounding patches have a high level of biomass – the quantity of fish caught will correspond to $x_{optimal}$, while in other cases – when the surrounding patches have a low level of biomass – the quantity of fish caught will be limited to 5% of the biomass of patches within the catchable range (x_{limit}). $x_{optimal}$ is higher for fishing vessels that engage in IUU activity, meaning that these vessels are more likely to be constrained in the quantity of fish that they catch.

It is worth noting that the value of x_{limit} varies significantly depending on the conditions in the surrounding patches. In circumstances where x_{limit} is lower than $x_{optimal}$ – both for legal and IUU fishing activities – the quantity of fish caught will be identical for all vessels. However, when x_{limit} is greater than $x_{optimal}$ for legal activities but less than $x_{optimal}$ for IUU activities, fishing vessels engaging in IUU activities will catch a greater quantity of fish than they would have were they acting legally. This is the mechanism via which IUU activities affect levels of biomass in the model, as shown in Figure 19 below.

Figure 19 Quantity of fish caught by legal and IUU fishing vessels under varying conditions



Market exit criteria

Each time fishing vessels return to port, they evaluate whether to remain in the market. This is based on their experiences in recent fishing trips. Specifically, **if the average profits per period across a full fishing trip fall below a certain threshold (taken as the weighted average cost of capital (WACC) multiplied by the fishing vessels' capital stock) for five consecutive periods, then fishing vessels will exit the market 25% of the time.** This criterion is summarised by the following decision rule:

*If average profits per period < capital stock x WACC for five consecutive periods: **exit market with 25% probability***

The WACC reflects the dividend that capital owners would expect to receive each period. It can also be thought of as the cost to fishing vessels of financing their assets. It is assumed that **each fishing vessels' capital stock is valued at 100,000 units** and the **WACC each period is 0.008%**. From a purely theoretical standpoint, it could be argued that fishing vessels should exit the market at the point at which profits fall below the cost of financing their assets. However, there are multiple sources of friction that exist in fishing markets that prevent this outcome from being realised, such as imperfect capital markets, transaction costs, imperfect information and irrational (non-profit maximising) actions.

Market entry criteria

Throughout the model simulations, it is assumed that there are potential fishing vessels waiting in the wings and ready to enter the market if the economic conditions are suitable. Each period, **if the average profit per period across the fishing fleet is greater than the start-up costs multiplied by the WACC, then there is a one in four chance that a new fishing vessel will enter the market**. The start-up cost is set to the same value (100,000) as the capital stock parameter described previously. This is because the majority of start-up costs in the fishing market can be accounted for by the cost of physical capital i.e. fishing boats and equipment. While this capital stock would be expected to depreciate without any active intervention, it is assumed that fishing vessels hold the value of their capital stock constant over time by investing in repairs and maintenance. The costs of this are reflected in the fixed cost parameter of the fishing vessels' cost function.

3). Enforcement agent parameters

While fishing vessels are able to move across the sea border in the ABM with varying degrees of freedom, enforcement agents' operations are confined to their own jurisdiction. For each model simulation, a pre-defined number of enforcement agents are distributed randomly across each country. These **enforcement agents then move forward by one patch each period**. In order to concentrate activity around ports – to reflect the higher amount of fishing that takes place in these areas due to lower travel times and costs – **each enforcement agent has a 5% probability each period of turning to face its home port**. This ensures that patches closer to ports are more heavily enforced but at the same time all areas of the model environment are patrolled to some extent. **Enforcement agents' radius of vision (the area within which they can detect IUU acts being carried out) is set to 5 patches in all bar one of the modelling scenarios (scenario O)**. This parameter had previously been varied in the original research, to reflect differences in the effectiveness of enforcement agents and / or the technologies deployed. However, it has been held constant in the most of the latest model simulations in order to isolate the effects of information sharing, which is the primary theme of interest.

5. Analysis of simulation results

One of the core characteristics of an agent-based model is that it generates highly path-dependent and often divergent outcomes. This is due to the interaction between agents and the way in which past events shape decisions in the future. For instance, fishing vessels are equipped with imperfect information regarding the risks of detection, meaning that their expectations are formed by past experiences rather than the actual detection probability. Therefore, if a high share of IUU activities happen to be detected and sanctioned early on during a model simulation, this can have a drastic impact on the number of illicit acts that are carried out in future periods due to the high perceived risk of detection (which may or may not align with the actual risk of detection). As a result of these types of phenomena, different runs of the same model scenario can deliver significantly different outcomes. In order to extract the underlying trends from individual model runs, each scenario has been run 50 times for 10,000 periods. The figures in this section present the average values of variables of interest over time across the 50 simulations that have been run for each scenario. Given the abstract and generalised nature of the model, the results presented below should not be interpreted as specific predictions of how fishery systems and fishing agents will respond to various policy interventions. The focus of the analysis is therefore on the relative movements that take place in the variables of interest over time and between different scenarios.

5.1 Homogeneous enforcement regimes (scenarios A – E)

The first series of scenarios examine the case in which the neighbouring coastal states have comparable enforcement regimes, both in terms of the number of enforcement agents, the capability of the enforcement agents (modelled as the radius within which they can detect IUU activities), the port capacity, and the fine rate imposed on fishing vessels that are found to have been conducting IUU activities. It is also assumed that fishing vessels are able to move freely across the border separating the two countries and can land their catch in either countries' port. In order to isolate the effects of information sharing, all other variables are held constant across each of the scenarios.

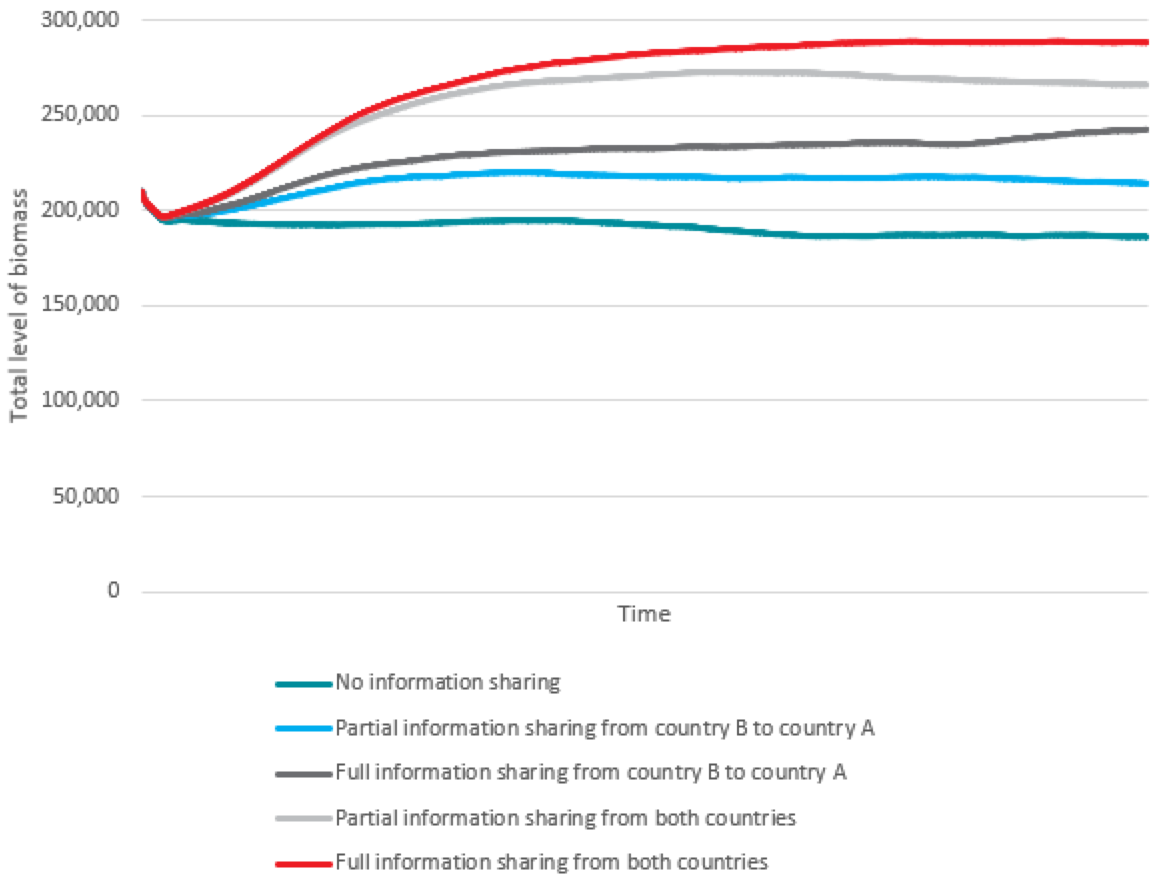
Total level of biomass

Figure 20 plots the average level of biomass across both countries over 10,000 periods for scenarios A to E. This demonstrates a clear and positive relationship between information sharing and the health of the fish population. In all the scenarios, the level of biomass briefly declines in the initial periods, as a high number of fishing vessels begin to extract from the previously unexploited fishery. However, the revised market exit and entry conditions mean that as the level of biomass diminishes, increasing numbers of fishing vessels experience losses and eventually leave the market. This in turn alleviates pressures on the fishery, allowing the level of biomass stabilise and then recover. It is after this point that the outcomes begin to diverge significantly across the different scenarios.

In the case of no information sharing (scenario A), the average level of biomass begins to decline from 210,170 at the beginning of the simulation to 186,122 at the end of the simulation. The improvements become visible even after a relatively limited amount of information sharing is introduced to the model. Indeed, in scenario B – which involves country B sharing the details of half of its detections with the port in country A – the average level of biomass at the end of the simulation is 214,010. This is 15% higher than in scenario A. Moreover, in scenario C – when country B shares all of its information with country A – the average level of biomass at the end of the simulation is 242,479, 30% higher than in scenario A. These results show that unilateral action to share information with neighbouring coastal states has the potential to boost the health of the fish population, with the size of the benefit rising in line with the amount of information that is shared. This holds even when the neighbouring countries decline to share their own information.

Scenarios D and E consider the case where both countries opt to share information with each other. In scenario D – when countries share the details of half of their detections – the average level of biomass is 266,068 at the end of the simulation. This compares to 214,010 in scenario B where only one country shares half of its information with the other. Scenario E represents the case of full information sharing between countries, which is effectively a pooling of enforcement resources between the two jurisdictions. Under this scenario, the level of biomass rises consistently after an initial drop, reaching an average level of 288,433 at the end of the simulation. This is 55% higher than in the case of no information sharing, underscoring the powerful role that this policy lever can have in supporting fish populations.

Figure 20 Total biomass level across both countries, scenarios A – E



Level of biomass in individual countries

The benefits of information sharing are not always distributed equally between the two countries. The dynamics involved are highly complex, with the actions and interactions of fishing vessels creating feedback loops that can be difficult to predict. Table 12 below outlines some of the differential impacts on country A and country B associated with one-way information sharing from enforcement agents in country B to the port in country A.

Table 12 Impacts of one-way information sharing from country B to country A

Country A	Country B
Due to the increased risk of detection from fishing illegally in country B and the unchanged risk of detection from fishing illegally in country A, country A becomes more attractive relative to country B as a location to carry out IUU activities. Therefore, information sharing from country B could drive fishing vessels with a tendency to conduct IUU activities from country B's waters to country A's waters. This in turn would increase the population of fishing vessels operating in country A, as well as the share of these fishing vessels conducting IUU activities. Both of these dynamics would weigh on the level of biomass in country A. Counteracting this effect is that information sharing from country B to country A can be expected to boost the level of biomass in country A by deterring IUU activities in country B. Since country A and country B share a common fishery, some of these benefits are likely to spill over into country A.	Information sharing increases the probability of detection for fishing vessels conducting IUU activities in country B. This is because, it prevents vessels from acting illegally in country B and then crossing the border to land their catch in country A without any risk of detection. As a result, IUU activities in country B's waters are disincentivised. Since vessels conducting IUU activities tend to catch more fish per trip (due to the nature of the cost curve), the result of information sharing boosts the level of biomass in country B in so far as it discourages IUU activity. There are two elements to this process: 1. Fishing vessels operating in country B's waters that were acting illegally now choose to act legally, thus lowering the amount of fish caught per trip. 2. Fishing vessels operating in country B's waters that were acting illegally now opt to conduct their IUU activities in country A's waters.

To illustrate these dynamics further, the flow chart in Figure 21 demonstrates a potential chain of events that could unfold in the case of one-way information sharing from country B to country A:

Figure 21 Example chain of events following unilateral information sharing from country B to country A

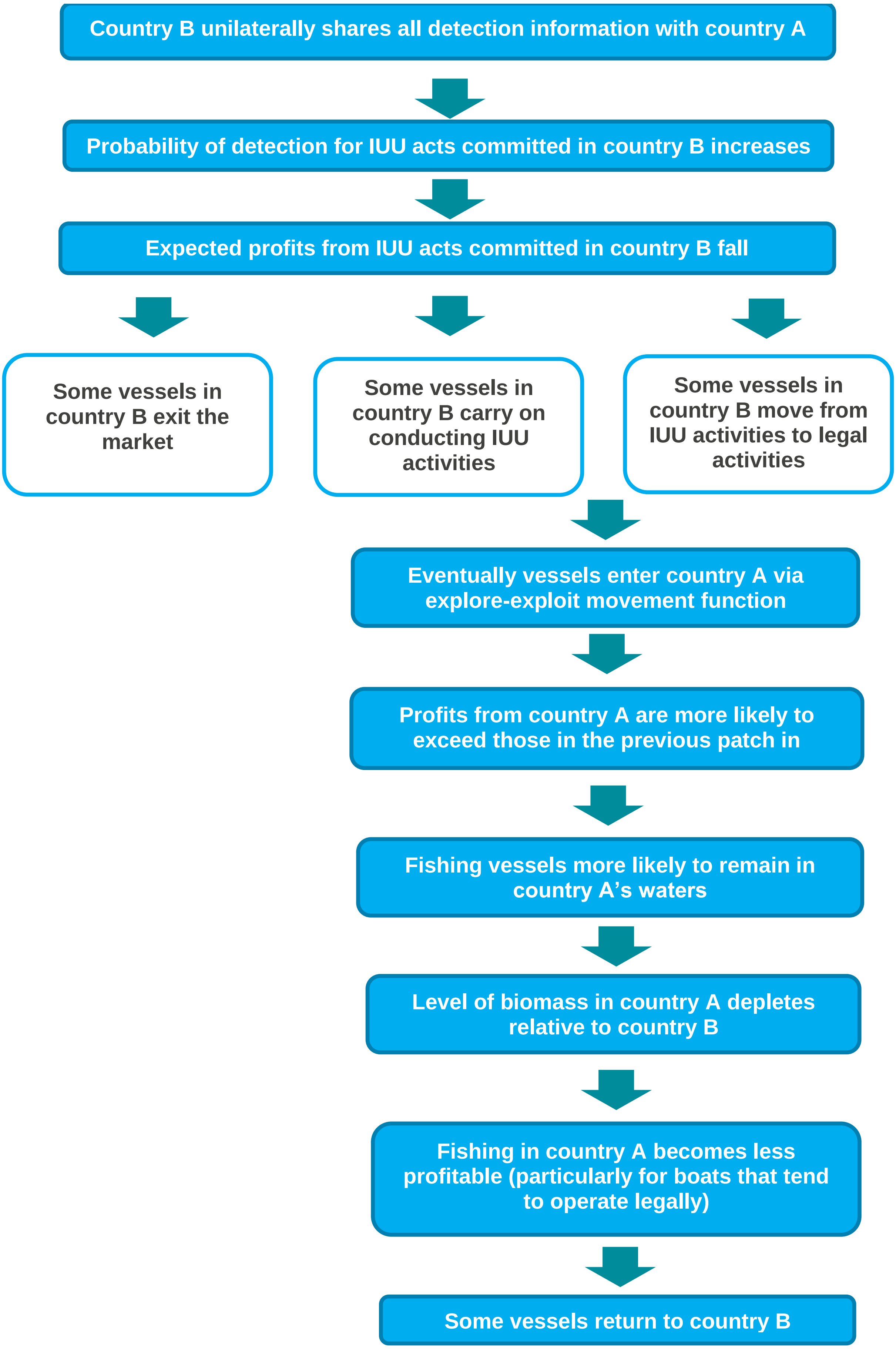
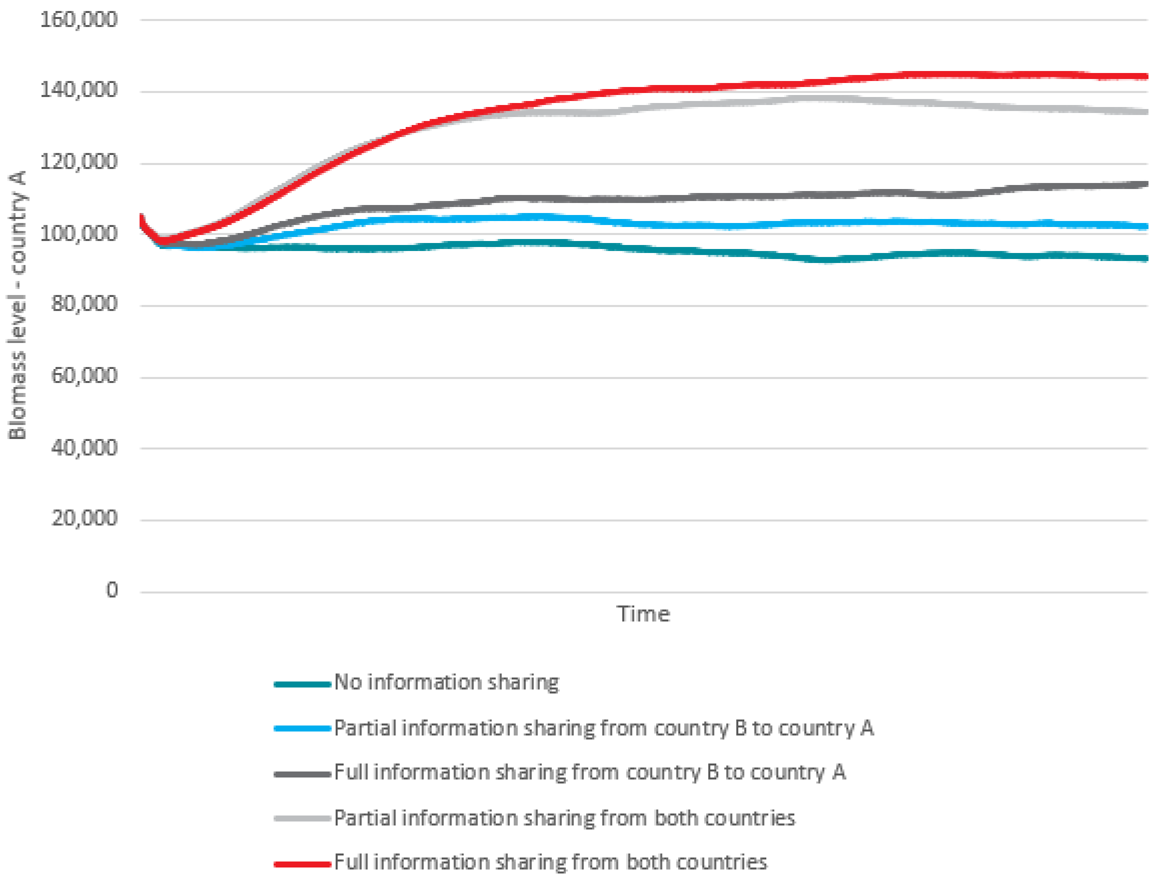


Figure 22 shows that the level of biomass in country A does pick up when country B shares some or all of its information unilaterally. At the of of the 10,000 period simulations, the average level of biomass in country A is 93,237 in scenario A (with no information sharing) compared to 102,184 in scenario B (when country B shares 50% of its information with country A) and 114,159 in scenario C (when country B shares all of its information with country A). This shows that even in the case of one-way information sharing, the recipient country is a net beneficiary despite some of the dynamics discussed in Table 12. However, the highest levels of biomass in country A are observed in scenarios where both countries share some or all of their information with the other. In scenario E, the long-run level of biomass in country A averages 144,236 – 55% more than the long-run average recorded in the case of no information sharing.

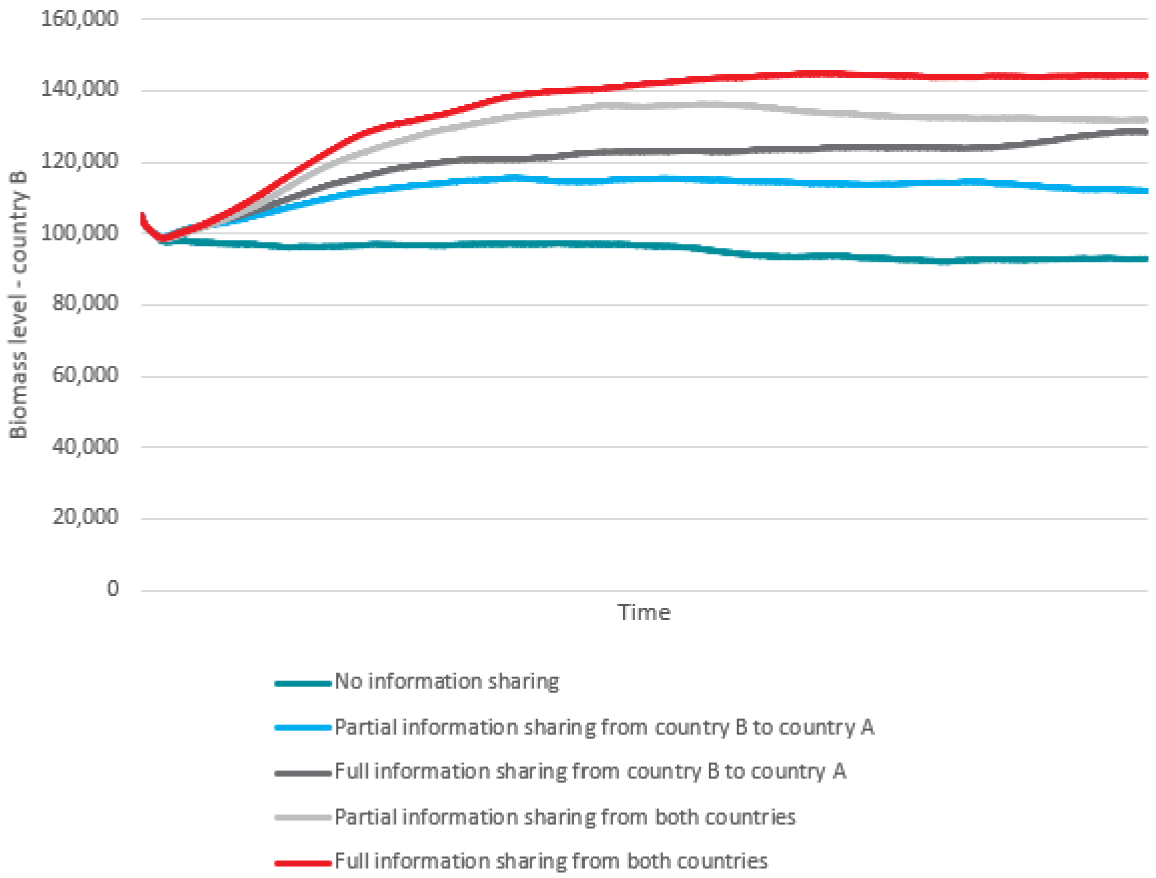
Figure 22 Level of biomass in country A, scenarios A - E



In country B, the level of biomass increases more notably between the case of no information sharing (scenario A) and the cases where country B shares 50% (scenario B) or all (scenario C) of its information with the port in country A. Indeed, at 128,320, the long-run level of biomass in country B in scenario C is 38% higher than in scenario A. By contrast, the level of biomass in country A rises by just 22% between scenario A and scenario C. This reflects the fact that the country sharing the information is the most direct beneficiary of the policy, since fishing vessels conducting IUU activities in its waters are now more likely to be detected. Crucially, this finding highlights that the sharing of information relating to IUU activity is not a case of the prisoner's dilemma, in which it is in neither party's individual self-interest to co-operate despite the mutual benefits that can be unlocked if they do. By contrast, the principal beneficiary of information sharing is the party sharing the information, meaning that equilibrium outcomes with high levels of co-operation are feasible – and indeed likely – if countries are equipped with the technological, operational and legal means to do so. However, it is important to note that countries consider a broad range of outcomes and policy objectives beyond the maximisation of biomass when designing their enforcement structures, meaning that these observations will not necessarily lead to co-operation between countries.

Turning to cases with information flowing in both directions, the long-run level of biomass reaches an average of 131,762 in scenario D (when both countries share information of half of their detections) and 144,197 in scenario E (when both countries share all of their information with the port of the neighbouring country).

Figure 23 Level of biomass in country B, scenarios A – E



Prevalence of IUU activities

A key metric when evaluating regulatory and enforcement policies is the degree to which they impact the prevalence of the activities they are designed to deter. This section examines the effects of information sharing on the rates of IUU activities observed in each country.

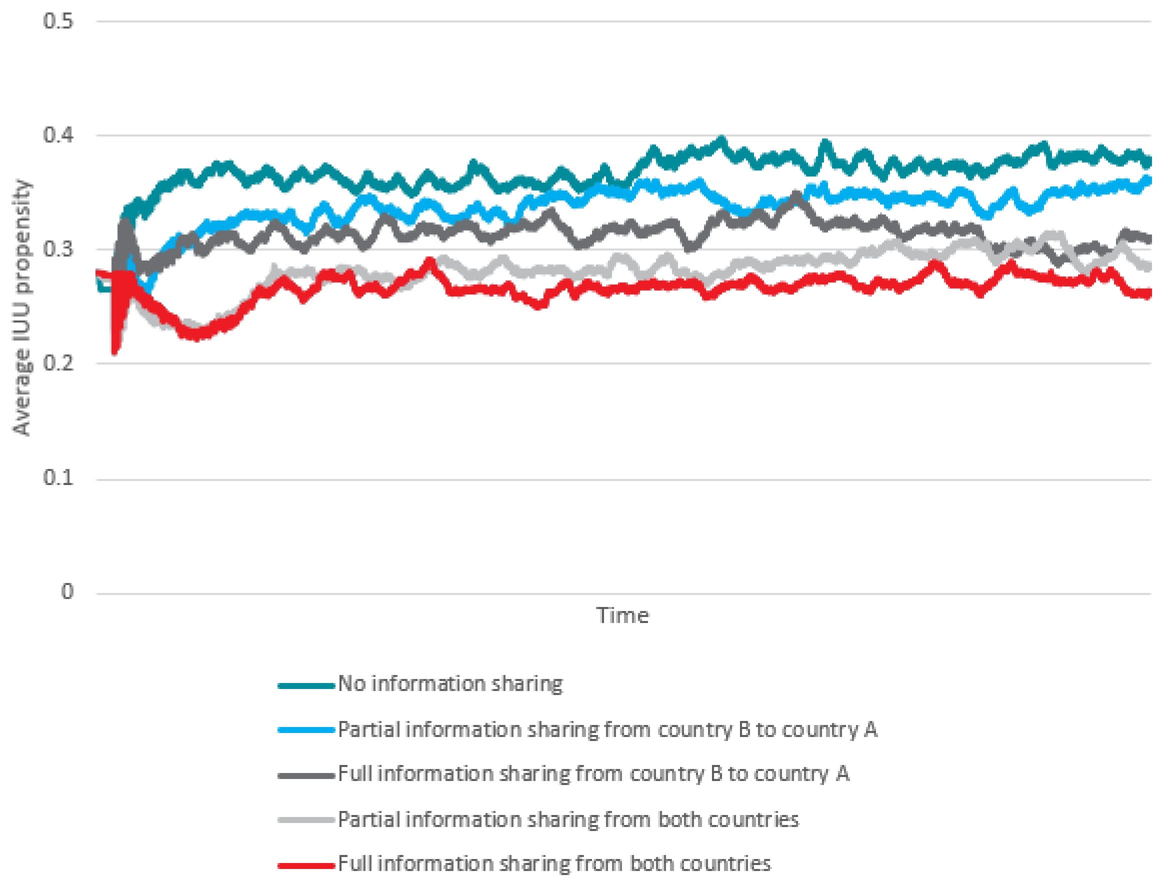
The introduction of the IUU-propensity parameter – described in detail in Section 3.2 – adds a layer of heterogeneity to the fishing vessels and their preferences. This means that specific policies can have differential impacts on the various fishing vessels in the model, depending on the extent of their aversion to conducting IUU activities. This in turn can trigger higher rates of market exit among specific groups of agents, changing the overall makeup of the population of fishing vessels in the long run.

The results of the simulations show that varying the level of information sharing that takes place between enforcement agents in the two countries has a significant impact on the characteristics of the participants in the fishing market. It can be observed that higher amounts of information sharing lead to a lower average IUU-propensity coefficient among the fishing vessels in the model. Indeed, in scenario E – where all information is shared in both directions – the average value of the IUU-propensity coefficient settles at around 0.26, indicating that the majority of fishing vessels are strongly disinclined to operate illegally. Meanwhile in the case of no information sharing (scenario A), the average value of the IUU-propensity coefficient among fishing vessels in the model hovers around 0.38.

This makes it relatively more likely for any given fishing vessel with a high IUU-propensity coefficient to exit the market – either due to a prolonged period of negative profits or a depletion of its wealth. This in turn means that a larger share of the population of fishing vessels are agents with a higher aversion to conducting IUU activities, reducing the population-average value of the IUU-propensity coefficient.

This finding has important implications for fishing vessels that tend to operate in a legal manner. Fisheries are able to support a finite number of active fishing vessels in equilibrium. If the number of fishing vessels exceeds the equilibrium level, the level of biomass will decline, making fishing activities less profitable and driving out the least successful vessels, eventually pushing the total count of fishing vessels back down towards the equilibrium level. This means that in fisheries with more lax enforcement structures in place, there is less room for fishing vessels with a strong preference to operate legally. This is due to a greater concentration of fishing vessels with a higher IUU-propensity coefficient.

Figure 24 Average value of IUU-propensity coefficient, scenarios A - E



The mechanism underlying the observed differences in the average value of the IUU-propensity coefficient across scenarios A – E is that information sharing creates a less favourable environment for fishing vessels that tend to operate illegally, due to a higher risk of detection. Table 13 presents the average detection probability after 10,000 periods for the four fishing strategies available to fishing vessels in the model:

1. Fishing in country A and landing catch at the port in country A;
2. Fishing in country A and landing catch at the port in country B;
3. Fishing in country B and landing catch at the port in country A;
4. Fishing in country B and landing catch at the port in country B;

It can be observed that in the absence of information sharing, the probability of sanctioning is zero when vessels conduct their fishing activities in one country and land their catch in the port of the other country. The detection probability associated with these cross-border fishing trips rises significantly when the country where the fishing is taking place begins to share its detection information with the neighbouring port. Indeed, the probability of being sanctioned after conducting IUU activities in country A before landing the catch at the port in country B rises from 0% in scenario C to 24% and 55% in scenarios D and E, respectively.

Note that the probabilities presented in Table 13 describe the chances that a fishing vessel that has conducted IUU activities at any point during a fishing trip is fined upon returning to the port. The probability of sanctioning is greater during fishing trips in which IUU activities have been carried across a high number of individual periods. The higher IUU-propensity of the fishing fleet in scenario A means that fishing vessels tend to conduct IUU activities for more periods during a fishing trip, which increases the overall probability of being sanctioned. This can be observed in the probability of sanctioning after conducting IUU activities in country A and landing the catch at the port in country A: in scenario A, the average detection probability over 10,000 periods is 63%, compared to 49% in scenario E.

Table 13 Probability of sanctioning for four fishing strategies, scenarios A - E

	Probability of being sanctioned after conducting IUU activities in country A's waters and landing catch at port in country A	Probability of being sanctioned after conducting IUU activities in country A's waters and landing catch at port in country B	Probability of being sanctioned after conducting IUU activities in country B's waters and landing catch at port in country A	Probability of being sanctioned after conducting IUU activities in country B's waters and landing catch at port in country B
Scenario A	63%	0%	0%	66%
Scenario B	60%	0%	17%	47%
Scenario C	61%	0%	54%	51%
Scenario D	51%	24%	20%	50%
Scenario E	49%	55%	55%	53%

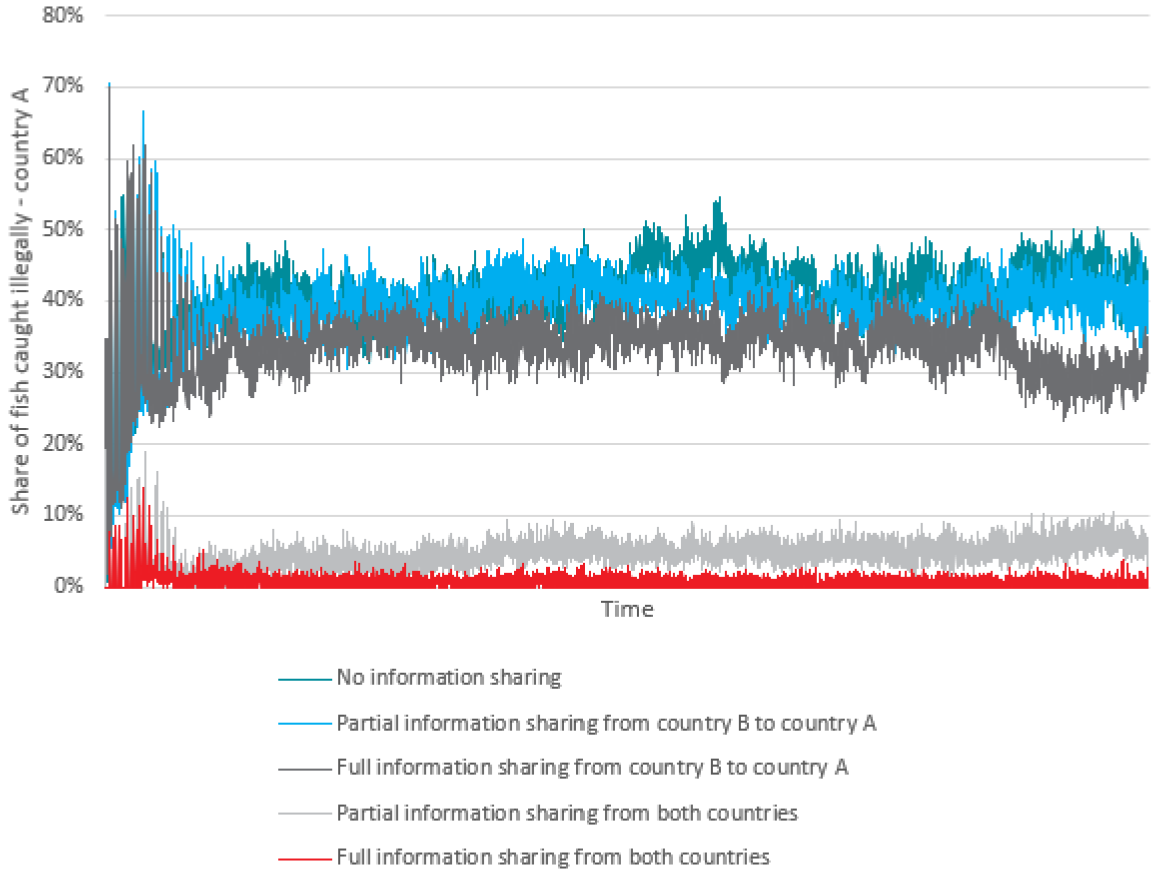
While the level of information sharing has been shown to affect the average characteristics of the participants in the fishing market, this is not tantamount to signalling an effect on the average behaviours of participants in the fishing market. This is because even fishing vessels with a high IUU-propensity coefficient may still choose to operate in a legal manner if the expected profits from doing so exceed those associated with IUU activities. In order to examine the impact of information sharing on fishing vessels' actions and behaviours, the share of fish caught illegally in each country has also been monitored under the various scenarios.

Considering first the case of country A, it can be seen that the share of fish caught illegally rises steadily to an equilibrium level of around 43% in scenario A where there is no information sharing between countries. The share of illegal fishing acts rises sharply during the early stages of the modelling runs in scenario A. This reflects the learning process that fishing vessels undergo, as they discover over time that the risk of detection following IUU activities is zero if they cross the border and land their catch in a separate jurisdiction to the one in which the illicit act was carried out.

In scenario A, a large share of the IUU activities taking place in country A's waters involve fishing vessels' operating illegally in country A before crossing the border to land their catch at the port in country B, where the risk of detection is zero due to the absence of any information sharing. This behavioural pattern is not affected directly by the introduction of unilateral information sharing from country B to country A (scenarios B and C), since the port in country B still does not have any information on the activities of fishing vessels that were carried out in country A. However, as shown in Figure 25, the introduction of unilateral information sharing does still affect the composition of the fishing fleet by lowering the average IUU-propensity coefficient. This means that the share of fish caught illegally in country A does decline marginally in scenarios B and C relative to scenario A, even though the incentives surrounding IUU fishing remain unchanged in country A's jurisdiction.

There is a dramatic change in scenarios D and E when country A begins to share information on the detections made by its enforcement agents with the port in country B. In scenario D – when country A shares half of its detection information with country B – the share of fish caught illegally settles around 6%. Meanwhile, in scenario E when there is full information sharing in both directions, illegal fishing activities are largely wiped out, with the share of fish caught illegally in country A remaining consistently below 1% in any given period.

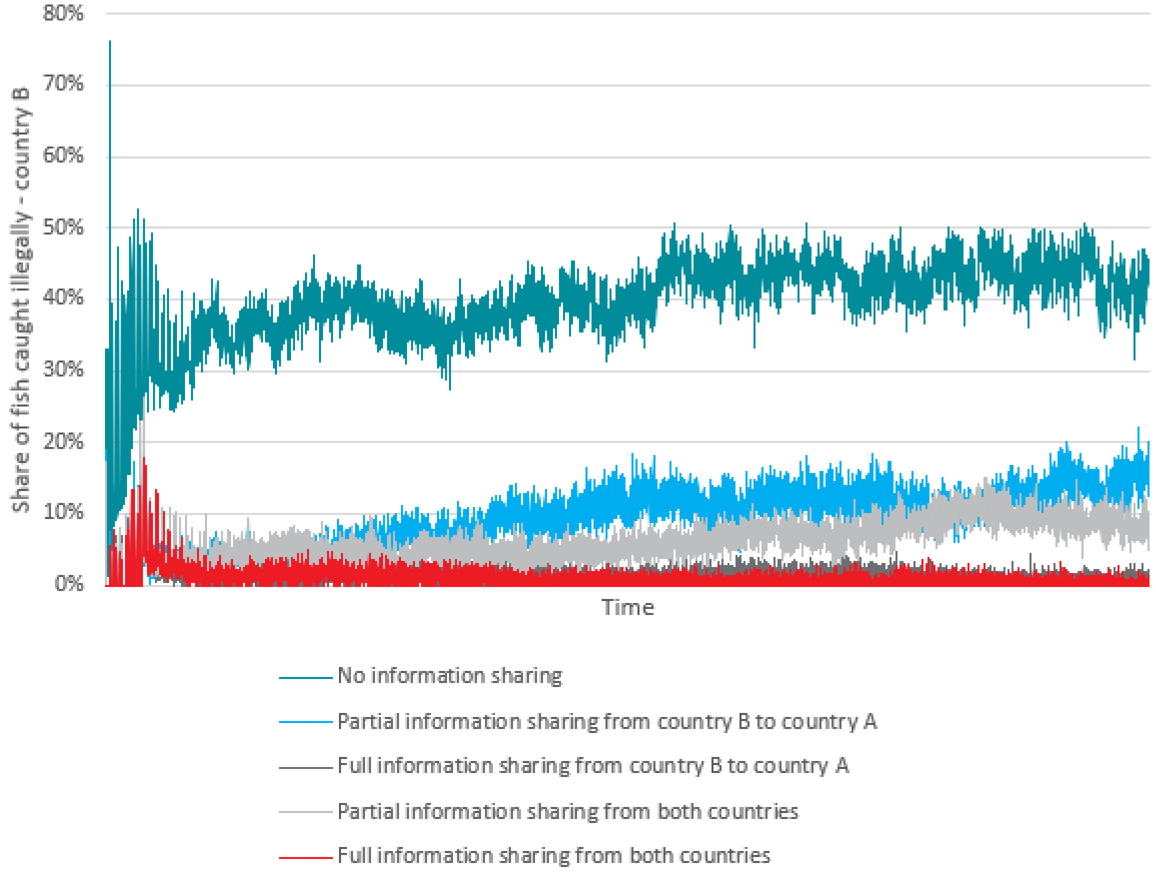
Figure 25 Share of fish caught illegally in country A, scenarios A – E



Scenario A models an environment in which there are symmetric enforcement structures in country A and country B. As a result, the share of fish caught illegally in country B also exceeds 40% on average at the end of the model simulation in the case of no information sharing. There is a considerable change in fishing vessels' actions when partial information sharing from country B to country A is introduced (scenario B), with the share of fish caught illegally in country B's waters dropping to around 17% by the end of the 10,000-period modelling run. This shows that a large portion of the benefits of information sharing can be achieved even if information on only half of detections are shared with ports in neighbouring countries. In the case of scenario C, the share of fish caught illegally during each period sinks to around 1%. Fishing vessels are discouraged from conducting IUU activities in country B's waters in scenarios B and C, since they are no longer able to operate illegally in country B and land their catch at the port in country A without the risk of being detected and subsequently sanctioned.

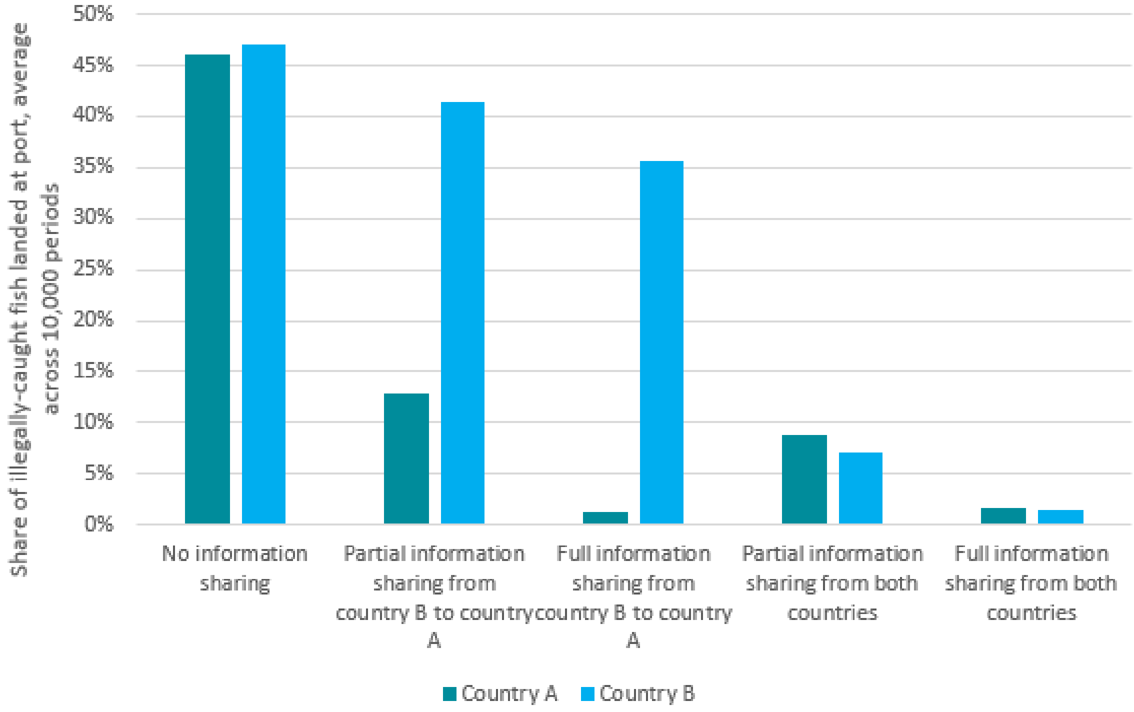
The difference between scenario B and scenario D is that in the former, only country B is sharing some of its information with its neighbour, whereas in the latter, both countries share some of their information. In scenario D, the share of fish caught illegally in country B's waters hovers around 10% - significantly below the share in scenario B. This can again be attributed to the change in the structure of the fishing fleet in scenario D, with the decision by country A to share detection information with country B creating an overall environment that makes IUU operations less attractive. Over time, this leads to a population of fishing vessels with a lower propensity to conduct IUU activities. As is the case in country A, the frequency of IUU activities is significantly reduced in scenario E, with the share of fish caught illegally in country B's waters remaining consistently below 1% on average.

Figure 26 Share of fish caught illegally in country B, scenarios A – E



Information sharing has a strong influence on the share of illegally-caught fish landed at each port. In scenario A, across the 10,000 periods, the average share of illegally-caught fish landed at the port in country A is 46%. The corresponding figure for the port in country B is 47%. In scenario C – where country B unilaterally shares all of its detection information with the port authority in country A – the share of illegally-caught fish landed at the port in country A averages 1% across the 10,000 periods. This compares to a figure of 36% for the port at country B. This discrepancy reflects the fact that information sharing by country B disincentives fishing vessels from crossing the border to land their illegal catch at the port in country A. However, the share of illegally-caught fish landed at the port in country B is still lower in scenario C than in scenario A. A key driver of this result is that when country B shares its detection information with the port authority in country A, there is an increase in the share of fish that is caught legally in country B's waters, which is more likely to be returned to the port in country B due to the lower time and travel costs.

Figure 27 Share of illegally-caught fish landed at ports, scenarios A - E



Fishery yield

The analyses above illustrate how the level of information sharing affects the prevalence of IUU fishing operations as well as the overall levels of biomass in each country. This section examines how these dynamics affect the yield of the fishery i.e. the quantity of fish caught each period. There are two main channels through which information sharing could theoretically impact fishery yields:

1. **Share of fish caught illegally:** the nature of the cost function for IUU fishing means that the size of the profit maximising catch is higher for fishing vessels acting illegally. This means that – all else being equal – a higher prevalence of IUU activity will tend to increase the yield of the fishery.

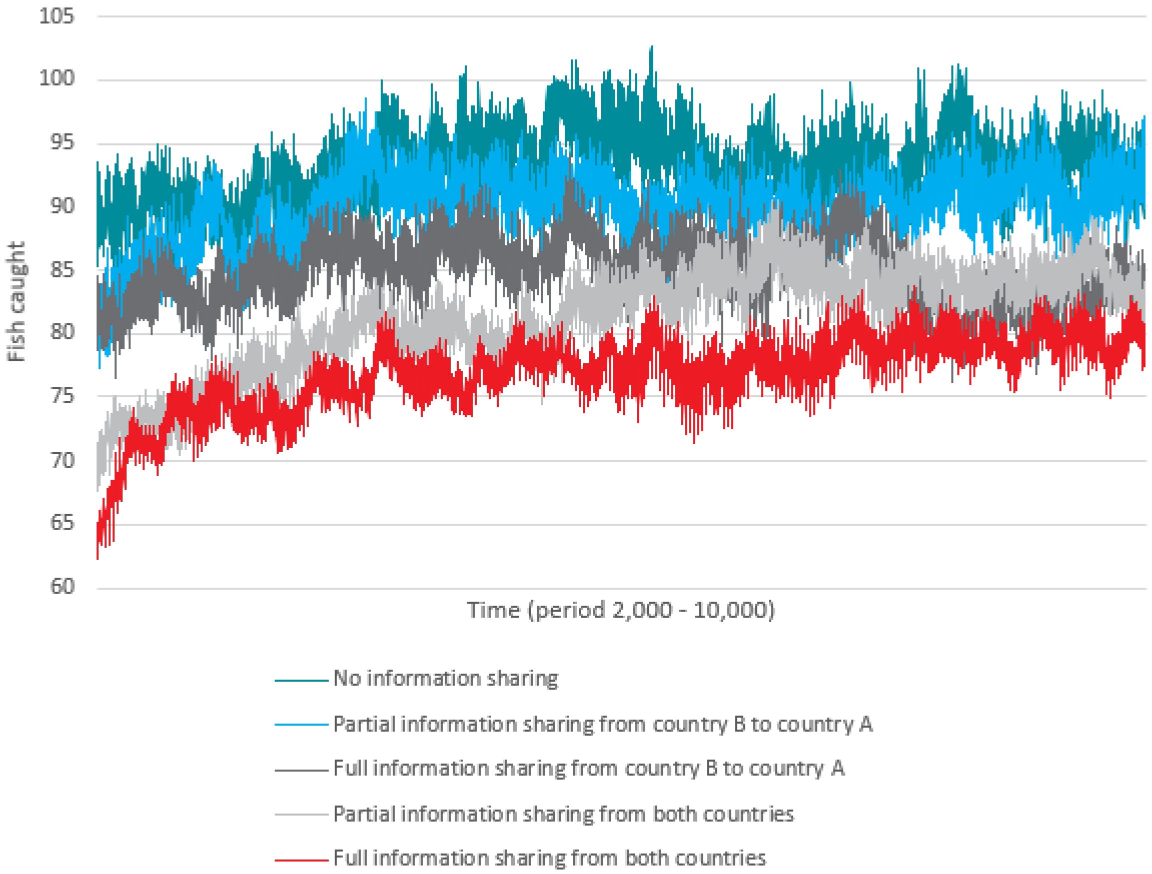
2. **Equilibrium level of biomass:** in the ABM, it is assumed that fishing vessels are capable of catching a fixed share of the biomass that is within their catchable range. If at least some fishing vessels are constrained by this factor, then environments with a higher density of biomass will generate a higher yield, since fishing vessels that are constrained (i.e. they cannot catch as much fish as they would like to each period) can catch a larger number of fish.

Figure 28 plots the average total catch of all fishing vessels each period for scenarios A to E. Note that in the early stages of the model, the average collective catch is typically very high, as the biomass in patches close to the ports has not yet been depleted. For clarity, the data has been presented for the final 8,000 periods of each modelling run.

In scenario A, the period catch of the fishing fleet largely remains above 90 units of biomass throughout the modelling simulations. Meanwhile in scenario B, the period catch of the fishing fleet starts off lower, but gradually converges towards the levels observed in scenario A at the end of the modelling simulations. This suggests that the effect of partial information sharing in discouraging IUU activity and thus lowering the fishery yield is eventually balanced by the higher level of biomass that can be supported in scenario B relative to scenario A, which facilitates larger period catches.

In scenarios C and D, the average total catch per period settles between 80 and 85, indicating that the reduced frequency of IUU activity (relative to scenarios A and B) overrides the effect of the higher level of biomass. Finally, in scenario E – where all information is shared by both countries – the active fishing vessels' collective catch hovers around 80 per period towards the end of the modelling simulations. By the final period, the average total catch in scenario E is 14% lower than in scenario A.

Figure 28 Fish caught during period, scenarios A – E



It is interesting to observe that the variability in the fishery yield across scenarios A to E is significantly lower than the variability in the total level of biomass, which increases by 55% between scenario A and scenario E. Moreover, while the total fishery yield declines in the scenarios with a greater degree of information sharing, a very different picture emerges when considering the total yield among fishing vessels operating legally. Indeed, the average amount of biomass extracted by legal means in the final period of scenario A is 49. This compares to 79 in scenario E. This is largely due to the very large share of fishing activities that are conducted legally in scenario E, which contrasts to scenario A where the majority of fish are caught illegally. These results show that the introduction of information sharing leads to a significant transfer of income from fishing vessels operating illegally to fishing vessels operating legally.

Figure 29 Fish caught legally during period, scenarios A – E

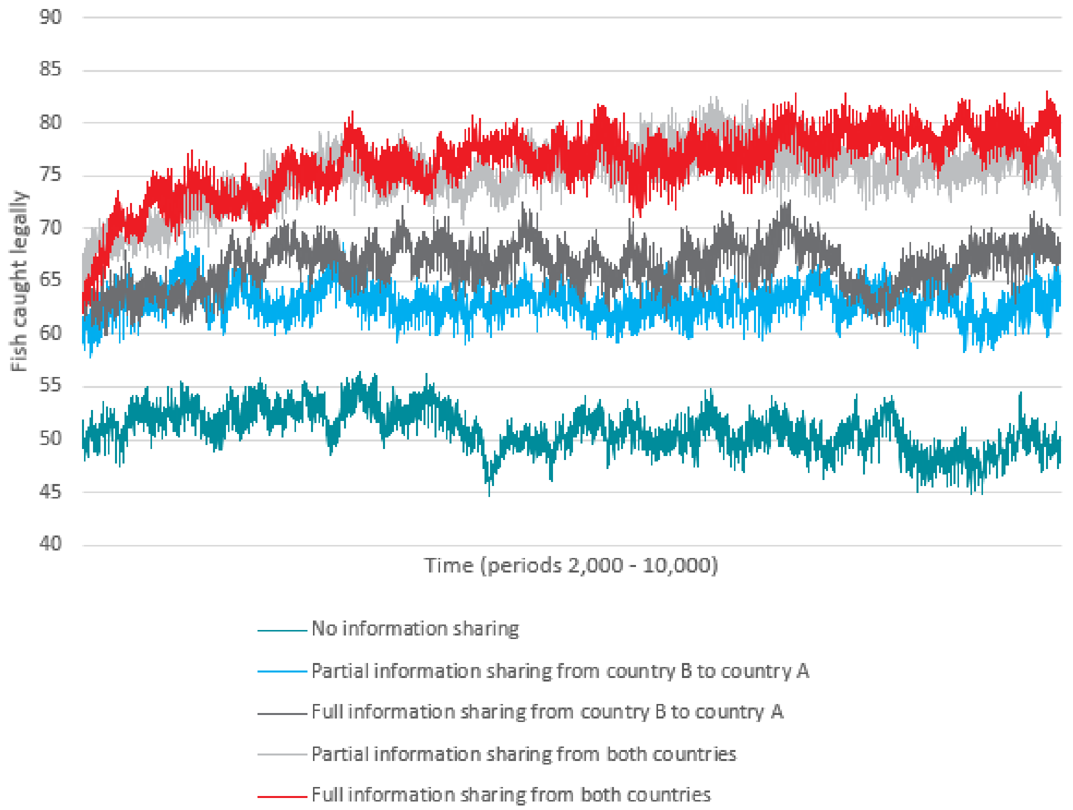
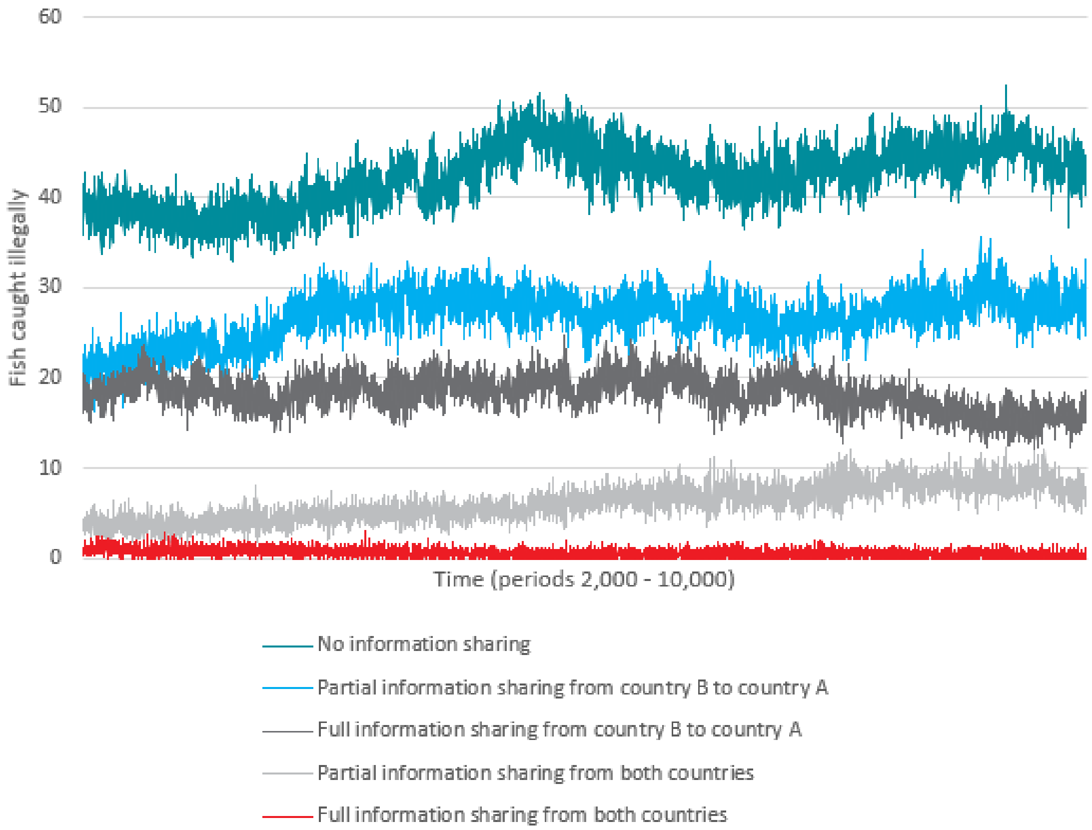


Figure 30 Fish caught illegally during period, scenarios A – E



Over the 10,000-period simulation, the average cumulative fishery yield over 50 iterations of scenario A is 965,348. The cumulative fishery yield declines steadily as the amount of information sharing in the model increases. However, the cumulative legal fishing yield is on average 42% higher in scenario E than in scenario A.

Table 14 Average cumulative fishery yield after 10,000 periods

	Fishery yield after 10,000 periods	Legal fishery yield after 10,000 periods	IUU fishery yield after 10,000 periods
Scenario A	965,348	550,373	414,974
Scenario B	921,236	667,156	254,081
Scenario C	874,093	693,660	180,432
Scenario D	828,302	773,050	55,252
Scenario E	790,925	783,664	7,261

Revenues from fines for IUU activity

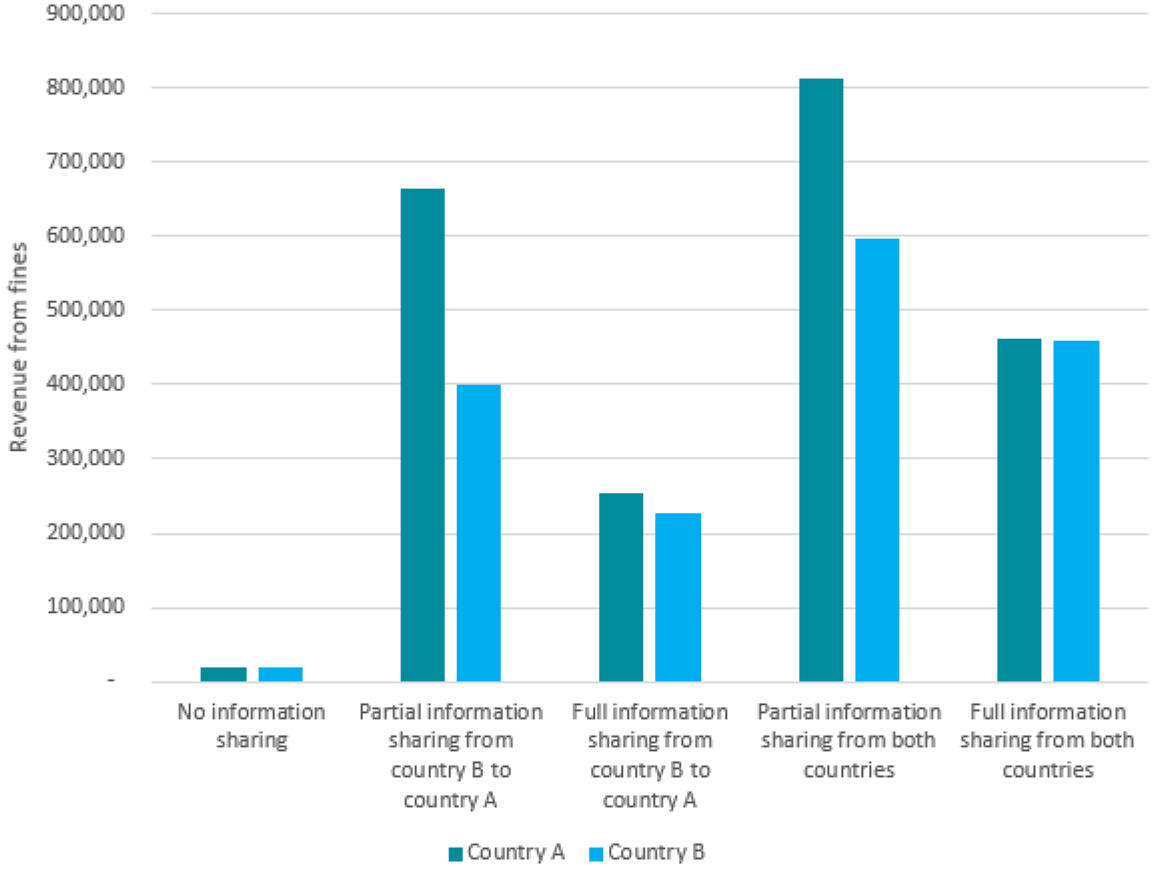
A relevant consideration when designing a regulatory and enforcement framework for a fishery is the revenues that are generated through the imposition of fines for fishing vessels that are found to have conducted IUU activities. These revenues can be used to fund more robust or efficient enforcement practices as well as measures to improve the overall health of the biological resources.

In scenario A – where no information sharing takes place – the cumulative revenues from fines are negligible for both countries. This is because the vast majority of illegal operations involve cross-border operations, for which the probability of detection is zero in the absence of information sharing. As information sharing is introduced, there are numerous dynamics at play which influence countries' revenues from fines. Firstly, the country receiving the information now has the opportunity to impose fines on fishing vessels that have conducted IUU activities in the neighbouring countries. Secondly, the deterrence of cross-border fishing operations drives some fishing vessels to land their catch at the port of the same country in which the IUU activities were carried out, providing a further source of revenues for those vessels that are detected. Counteracting these effects is the fact that higher levels of information sharing lead to an overall reduction in the share of fish that is caught illegally, which weighs on the revenues received from fines for IUU activity. Figure 31 shows that the peak revenues are received in scenarios with partial information sharing. The intuition behind this finding is that the information sharing creates an opportunity for fishing vessels that have operated illegally to be detected while at the same time not generating enough of a deterrent to wipe out the practice altogether.[43]

43 Revenues from fines vary considerably between different modelling runs, leading to volatility even when averaging across 50 simulations. For instance, the average fine revenues are significantly higher for country A than country B in scenario D, despite the symmetrical enforcement structures.

It is also interesting to observe that revenues from fines remain relatively high in both countries, even when there is full information sharing between both countries (scenario E). Although the prevalence of IUU fishing is far lower in scenario E than in scenario D, the probability of detection and sanctioning is significantly higher in scenario E, which drives up the revenues from fines and partially offsets the effect of lower IUU fishing activity.

Figure 31 Average revenue from fines after 10,000 periods, scenario A - E



5.2 Heterogeneous enforcement regimes (scenarios F – J)

The results described above for scenarios A – E highlight the profound impact that information sharing can have in cases where there are two countries with similar enforcement capacities and approaches. However, there are numerous instances where a country with a highly rigid enforcement structure shares a sea border with one with a more lenient regulatory framework. Scenarios F – J consider cases in which country A halves the number of enforcement agents patrolling its waters from 10 to 5. This heterogeneity has numerous potential implications. Firstly, it could shift the balance of IUU fishing activities towards the low enforcement jurisdiction. Meanwhile, the corresponding depletion of biomass in the low enforcement country could see fishing vessels with a tendency to operate legally gravitate towards the higher enforcement jurisdiction where there is a healthier fish population. Furthermore, introducing a looser regulatory framework in country A could conceivably lead to a fishing fleet with a lower aversion to IUU activities, placing a strain on the level of biomass in both countries. These dynamics indicate that the limitations faced by country A in maintaining high regulatory standards not only affect outcomes within its own territory – they also generate numerous externalities (both positive and negative) on the neighbouring coastal state.

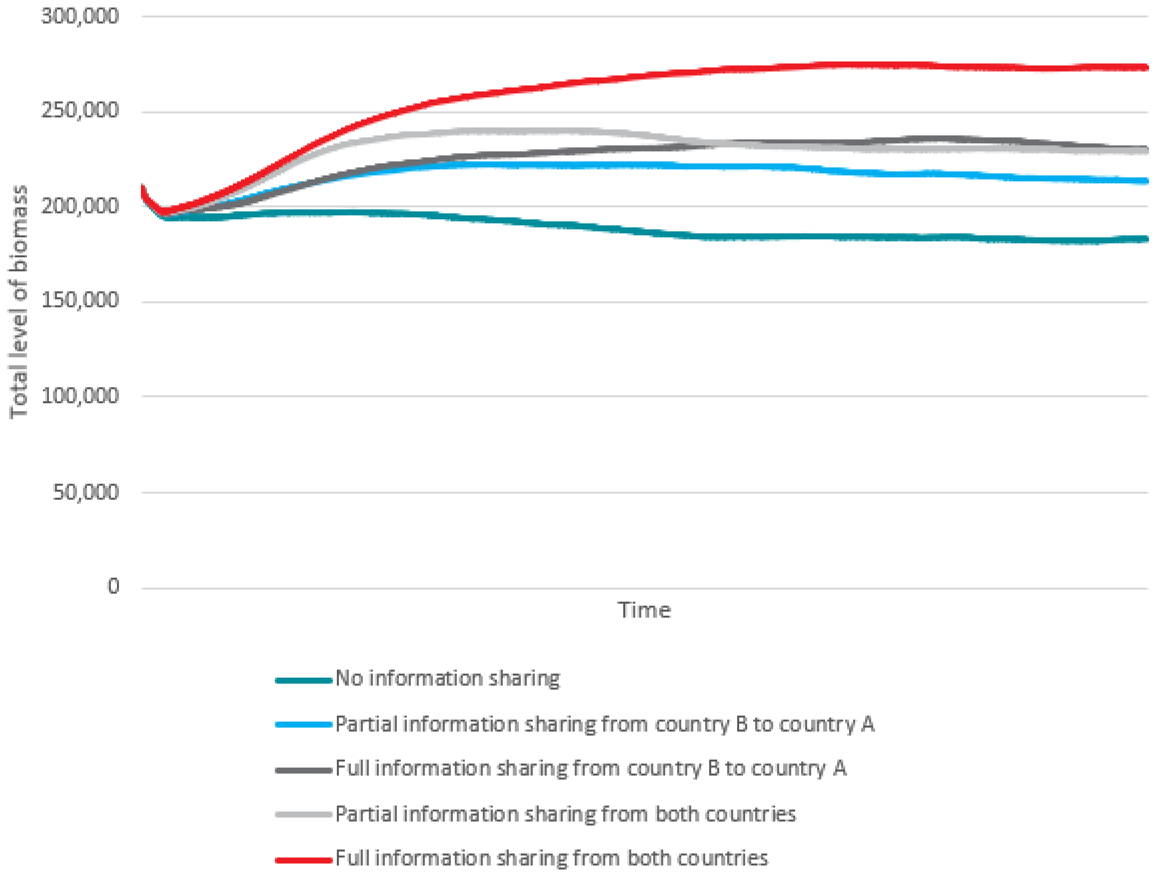
Total level of biomass

As is the case with homogeneous enforcement regimes, increasing levels of information sharing in the heterogeneous framework consistently and significantly elevates the long-run level of biomass across the two countries. In the case of no information sharing (scenario F), the total level of biomass declines slightly during the earlier stages of the simulation, before settling at around 183,000. Interestingly, this level is not significantly different to the long-term outcome from scenario A, despite a lowering of the overall number of enforcement agents from 20 to 15. This is a likely consequence of the fact that in conditions with a porous border and no information sharing between jurisdictions, the ability of individual countries to deter IUU activities unilaterally through changes to the domestic regulatory structure is significantly diminished, since most IUU activity involves boats crossing borders to land illegally obtained fish in order to remove the risk of detection. These findings therefore indicate that in the absence of information sharing, the impacts of unilaterally altering regulatory and enforcement frameworks at a domestic level are largely stymied.

There is a similar story in cases where the high enforcement country (country B) shares some or all of its information with country A (scenarios G and H). In scenario G, the long-run level of biomass is similar to that in scenario B, while the long-run level of biomass does not differ dramatically between scenarios C and H, despite the variation in the total number of enforcers. The intuition behind these results is that when country B unilaterally decides to share information on detections with the port in country A, the corresponding change to fishing vessels' profit functions means that most illegal actions involve IUU activities being conducted in country A with catch being landed in country B. The expected profits of this type of action are not impacted by the number of enforcement agents in country A's waters, since none of the detections they record are shared with country B where the catch is ultimately landed.

The effects of reducing the overall number of enforcement agents become more discernible in scenarios where country A shares some (scenario I) or all (scenario J) of its information with the port authorities in country B. In scenario I – where both countries share with each other information on half of the detections that they make – the total level of biomass is just over 229,000 on average after 10,000 periods. This compares to a long-run level of around 266,000 in scenario D, which demonstrates a considerable effect associated with country A lowering the number of enforcement agents in its waters. Meanwhile in scenario J – where all information is shared by both countries – the long-run level of biomass settles at a level around 273,000 on average, compared to around 288,000 in scenario E.

Figure 32 Total level of biomass, scenarios F – J



Level of biomass in individual countries

The scenarios analysed above indicate that a lowering of enforcement standards in country A does have a significant impact on the total level of biomass in circumstances when there is bilateral information sharing. One might expect that the worst effects would be largely felt in the country with the lower level of enforcement, since this change makes IUU fishing activities relatively more attractive. Moreover, there is an argument that the health of the fishery in country B could be boosted as a result of country A's lowered standards, since fishing vessels will favour carrying out their IUU activities in country A's waters.

Table 15 below shows that while this is true to some extent, in the case of full information sharing, more than a third (38%) of the decline in biomass that follows a reduction in the number of enforcement agents in country A takes place in country B. This therefore represents a significant negative externality imposed by country A on country B.

It is also interesting to observe that the difference in the long-run level of biomass between scenario E and scenario J is far smaller than the difference between scenario A and scenario E. This suggests that transitioning from no information sharing to full information sharing has a greater impact on biomass levels than transitioning from having 5 enforcement agents in country A to having 10 enforcement agents. This is because in scenario A, the lack of information sharing means that the probability of detection becomes zero once fishing vessels that have operated illegally cross the border to land their catch. The effect of this is therefore almost equivalent to removing all enforcement agents from both countries. Moreover, the marginal increase in detection probability diminishes as the number of enforcement agents increases. This is because the enforcement agents do not co-ordinate their movements, meaning that there is a growing likelihood that multiple enforcers are patrolling the same area of water at any given time as the number of agents increases.

Table 15 Impacts of lowering enforcement standards in country A

	Average level of biomass after 10,000 periods		Change in long-term biomass due to lowering of enforcement standards in country A
	Homogeneous enforcement regimes (scenario E)	Looser enforcement regime in country A (scenario J)	
Country A	144,236	134,815	9,421
Country B	144,197	138,404	5,793

In the case of partial information sharing between both countries (scenarios D and I), 30% of the decline in total biomass associated with a lowering of enforcement standards in country A is experienced in country B's waters. There are numerous possible explanations for why a unilateral reduction in enforcement in one country can impact levels of biomass in the waters of its coastal neighbour:

- The fish population consists of moving entities that are oblivious to any sea border. Therefore, a depletion of biomass in one country will eventually be felt in the waters of a coastal neighbour, as biomass diffuses across the model environment from areas of high biomass density to areas of low biomass density;
- Lower levels of enforcement in one country would lead to an increased share of fishing vessels with a tendency to commit IUU acts. While it would be expected that these vessels would concentrate in country A's waters, there will be cases where they stray into country B's waters as well;
- When biomass levels in the low enforcement country become severely depleted (in part because of a reduced level of enforcement), the higher enforcement country becomes more attractive to fishing vessels. This will have an equalising effect on levels of biomass in the two countries.

Figure 33 Level of biomass in country A, scenarios F – J

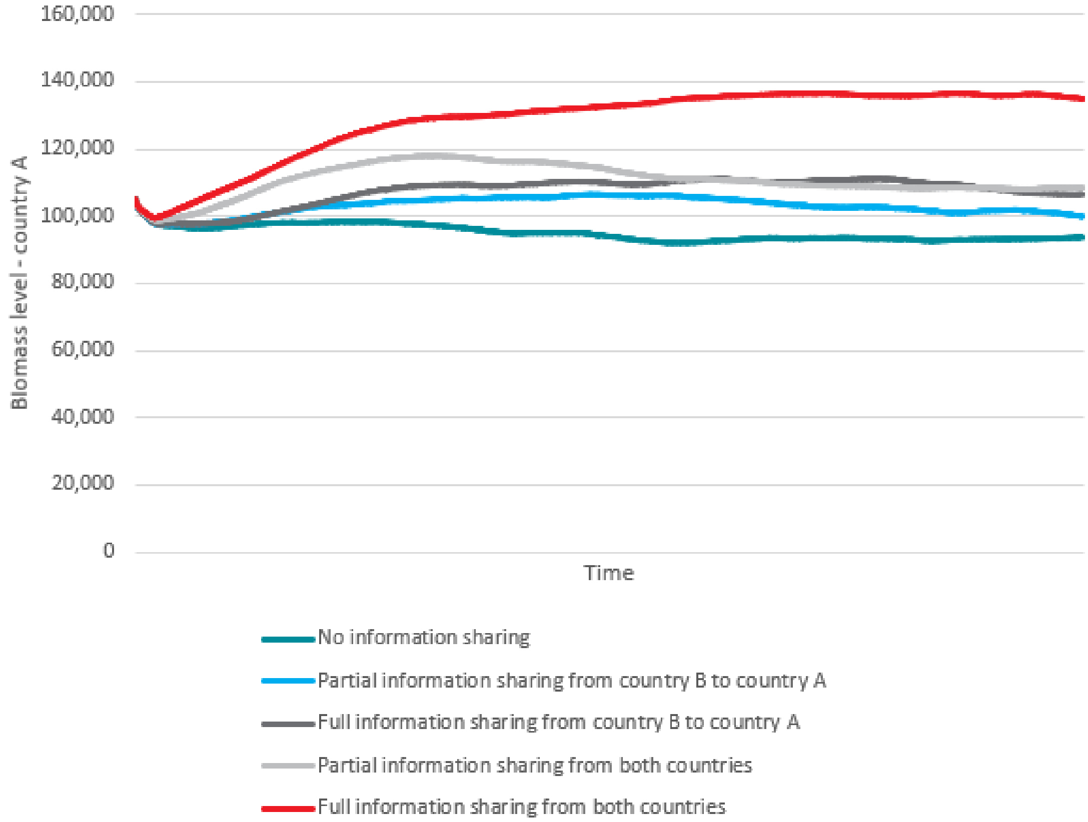
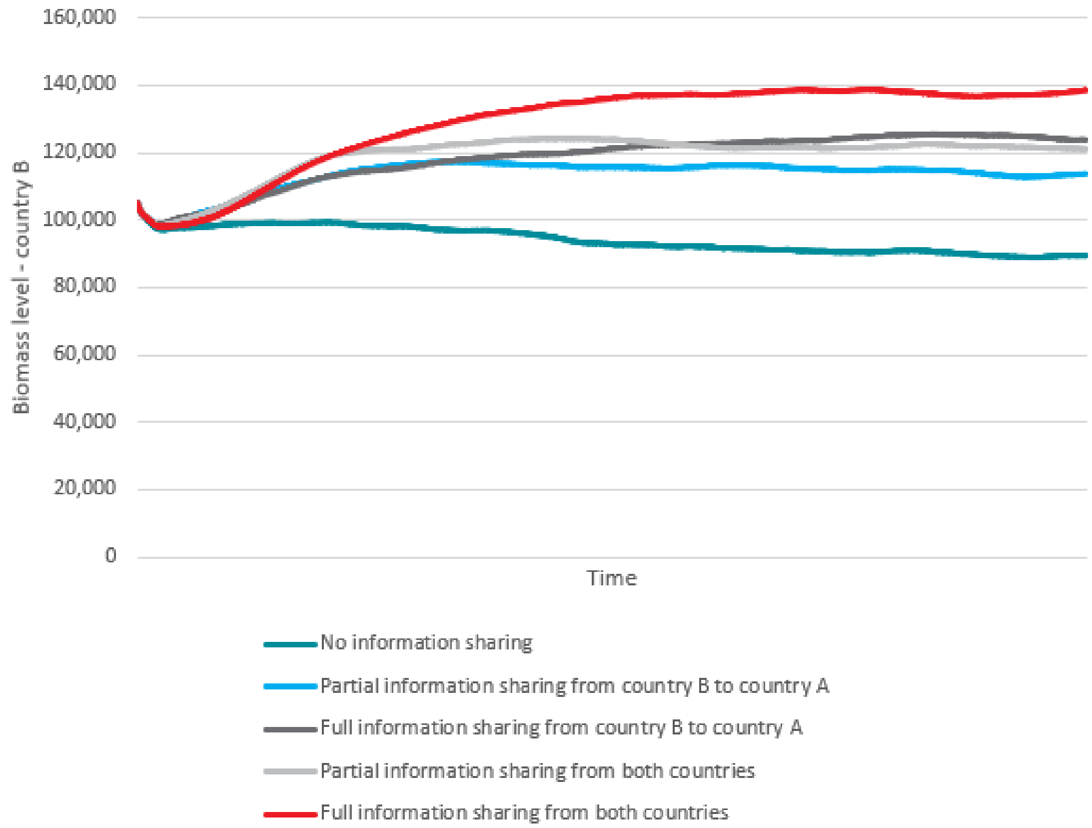


Figure 34 Level of biomass in country B, scenarios F – J

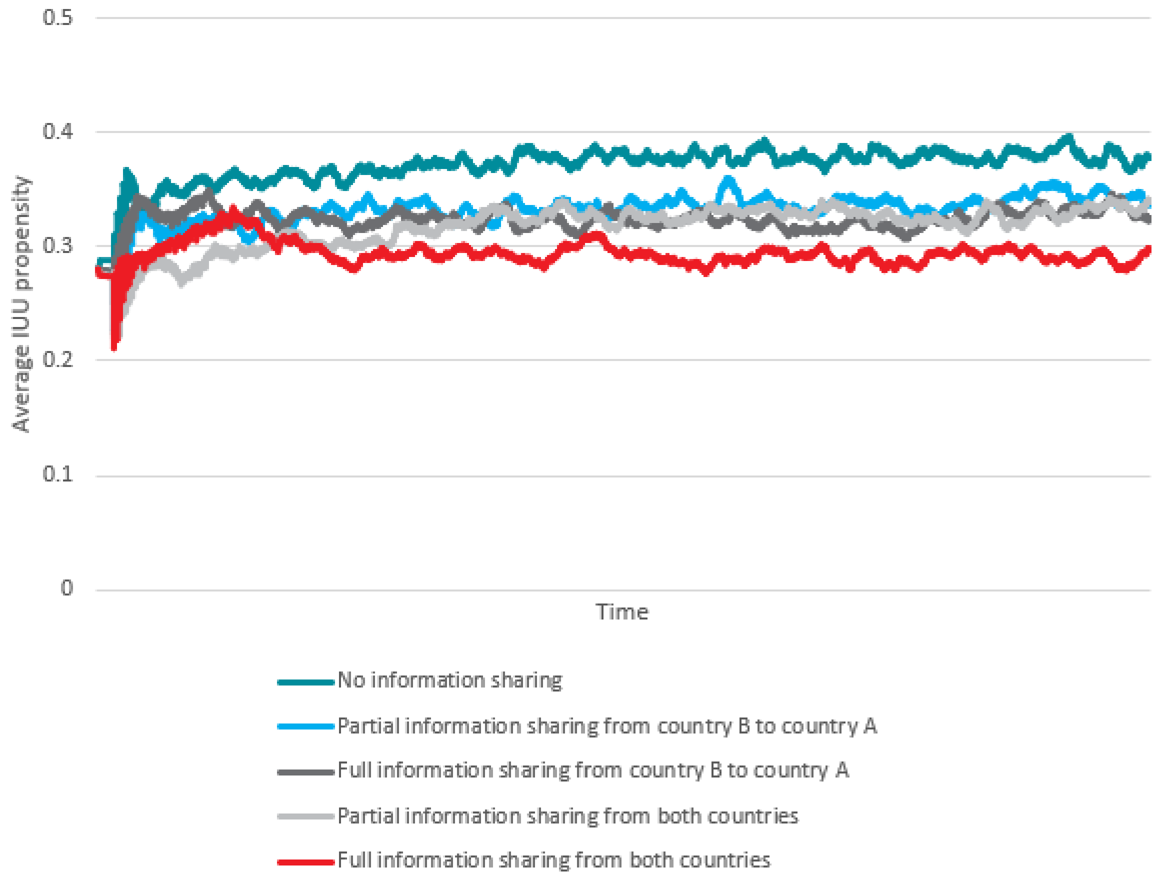


Prevalence of IUU activities

The results of the simulations show that in the case of heterogeneous enforcement regimes, the structural characteristics of the fishing fleet as a whole varies depending on the degree of information sharing taking place. In the case of no information sharing (scenario F), the average value of the IUU-propensity coefficient settles at around 0.38. This is comparable to the average observed in scenario B, where there is no information sharing but homogeneous enforcement regimes. This again reflects the fact that under circumstances in which vessels can move freely across maritime borders but there is no exchange of information between the two countries, IUU activities predominantly involve fishing in one jurisdiction and landing the catch in the other. These cross-border activities are broadly unaffected by the number of enforcement agents in either territory, since the probability of detection after crossing into the other country is zero.

However, the reduction in the number of enforcement agents in country A does have a discernible impact on the average value of the IUU-propensity coefficient among the fishing fleet in scenarios where there is information flowing across the border in both directions. Indeed, in scenario I (partial information sharing from both countries), the average value of the IUU-propensity coefficient reaches 0.34 by the end of the 10,000 period simulations. This compares to an average of 0.29 in the case of scenario B, which is identical except for the presence of five additional enforcement agents in country A's waters. Similarly, the average value of the IUU-propensity coefficient in scenario J (with full information sharing from both countries) is 0.30, compared to 0.26 in the equivalent case with higher enforcement in country A (scenario E).

Figure 35 Average value of IUU-propensity coefficient, scenarios F – J



Increased levels of information sharing generally brings down the share of fish that are caught by illegal means. The results for the scenarios with heterogeneous enforcement regimes do not differ significantly from the equivalent scenarios with homogenous enforcement regimes in the case of the high enforcement country (country B). The share of fish caught illegally in country B towards the end of the 10,000 period simulation drops from an average of around 43% in the case of no information sharing (scenario F) to less than 1% in the case of full information sharing (scenario J). This is similar to the figures observed in the equivalent scenarios with homogeneous enforcement between the countries.

For the low enforcement country (country A), there is a more sizeable difference in outcomes between the heterogeneous scenarios and the equivalent homogeneous scenarios. As is the case in the homogeneous framework, country B unilaterally increasing information sharing does not have a significant impact on the share of IUU fishing conducted in country A's waters. However, the share of fish caught illegally in scenarios G – H is slightly higher than in scenarios B – C. This is because in scenarios G – H, there are half as many enforcement agents in country A's waters, meaning that the expected profits from IUU activities are higher relative to the expected profits from legal operations for those vessels that choose to both fish and land their catch in country A.

The most notable finding, however, is the more muted effect that bilateral information has in reducing IUU activities in country A when the number of its enforcement agents is halved. Indeed, in scenario I – with partial information sharing from both countries – around 35% of fish caught in country A are done so by illegal means in the long-run. This compares to just 5% in scenario D, which is identical to scenario I apart from the fact that country A has twice the number of enforcement agents. Even when there is full information sharing from both countries (scenario J), the share of fish caught illegally in country A still hovers around 8% on average after 10,000 periods of the simulation. This compares to less than 1% typically in the equivalent scenario with double the number of enforcement agents in country A (scenario E).

These findings are due to the higher average value of the IUU-propensity parameter in the case of heterogeneous enforcement regimes, as well as a reduction in the probability of detection in country A's waters. Table 16 shows that the probability of being sanctioned for fishing vessels that have conducted IUU activities in country A's waters is significantly lower across all of the scenarios relative to the case when country A has 10 enforcement agents rather than 5.

Table 16 Probability of sanctioning associated with four fishing strategies, scenarios F - J

	Probability of being sanctioned after conducting IUU activities in country A's waters and landing catch at port in country A	Probability of being sanctioned after conducting IUU activities in country A's waters and landing catch at port in country B	Probability of being sanctioned after conducting IUU activities in country B's waters and landing catch at port in country A	Probability of being sanctioned after conducting IUU activities in country B's waters and landing catch at port in country B
Scenario F	39%	0%	0%	55%
Scenario G	46%	0%	17%	52%
Scenario H	46%	0%	52%	50%
Scenario I	39%	11%	20%	56%
Scenario J	25%	40%	50%	48%

These results highlight that even in the case of a highly integrated fishery with information sharing between jurisdictions, countries' unilateral decisions on setting their regulatory regimes can nonetheless have a significant impact on the prevalence of IUU fishing in their own jurisdiction.

Figure 36 Share of fish caught illegally in country A, scenarios F – J

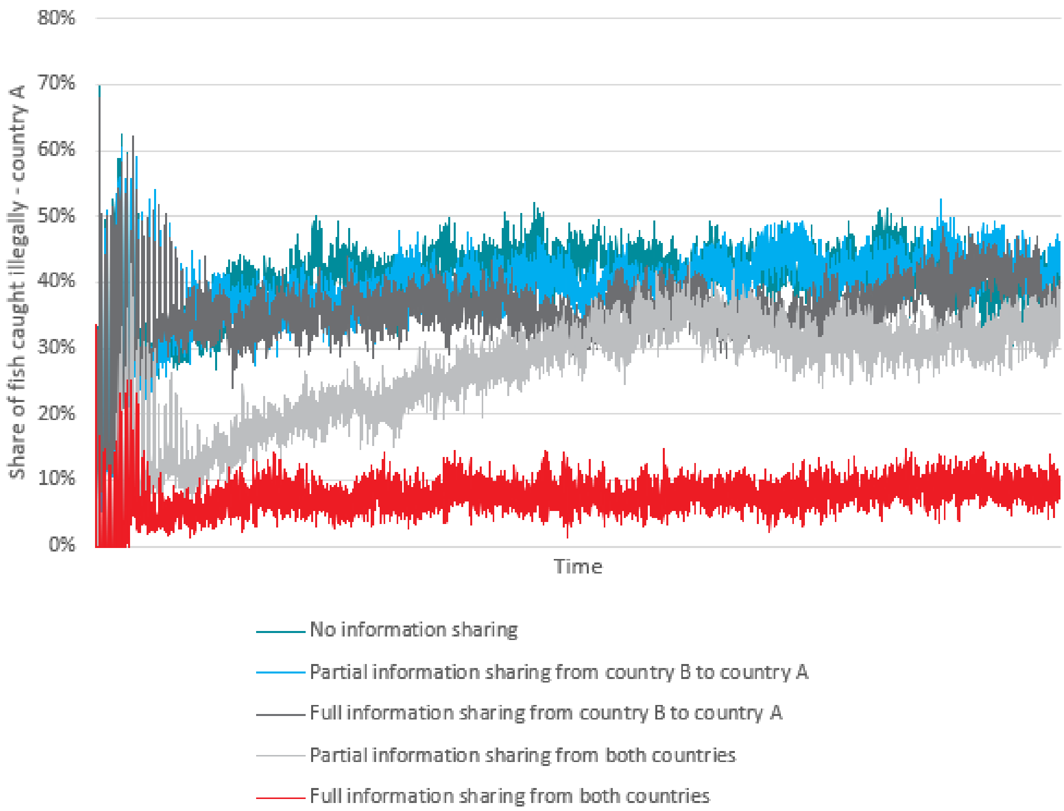
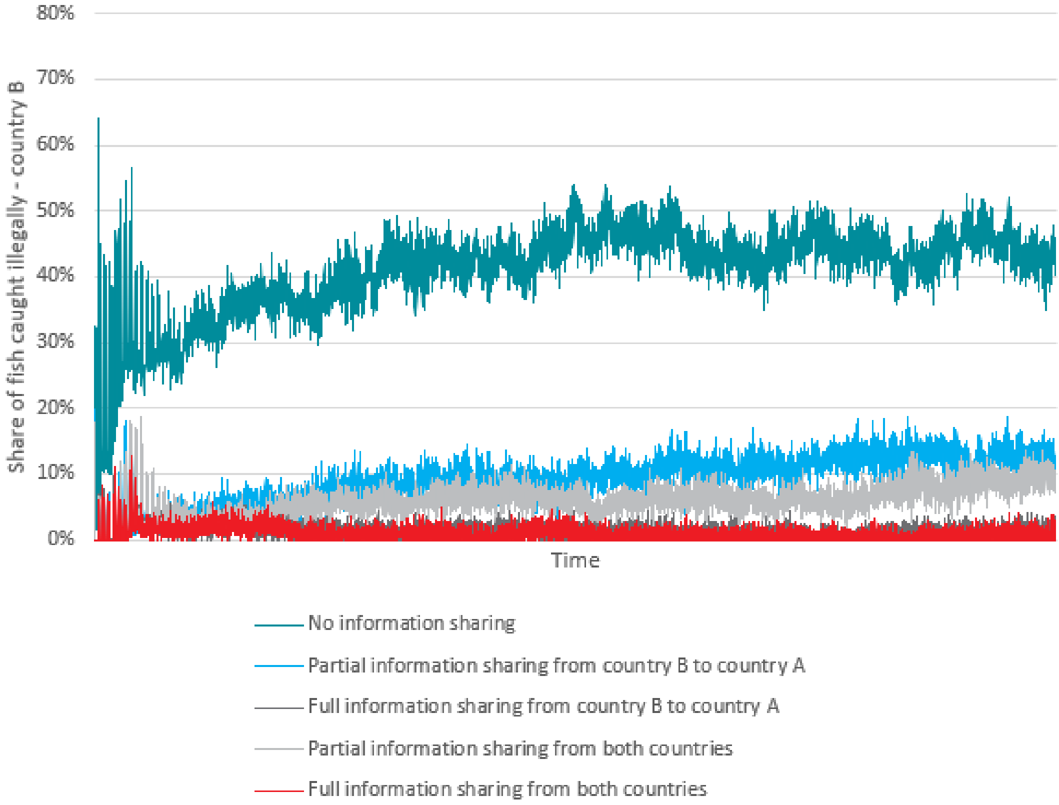
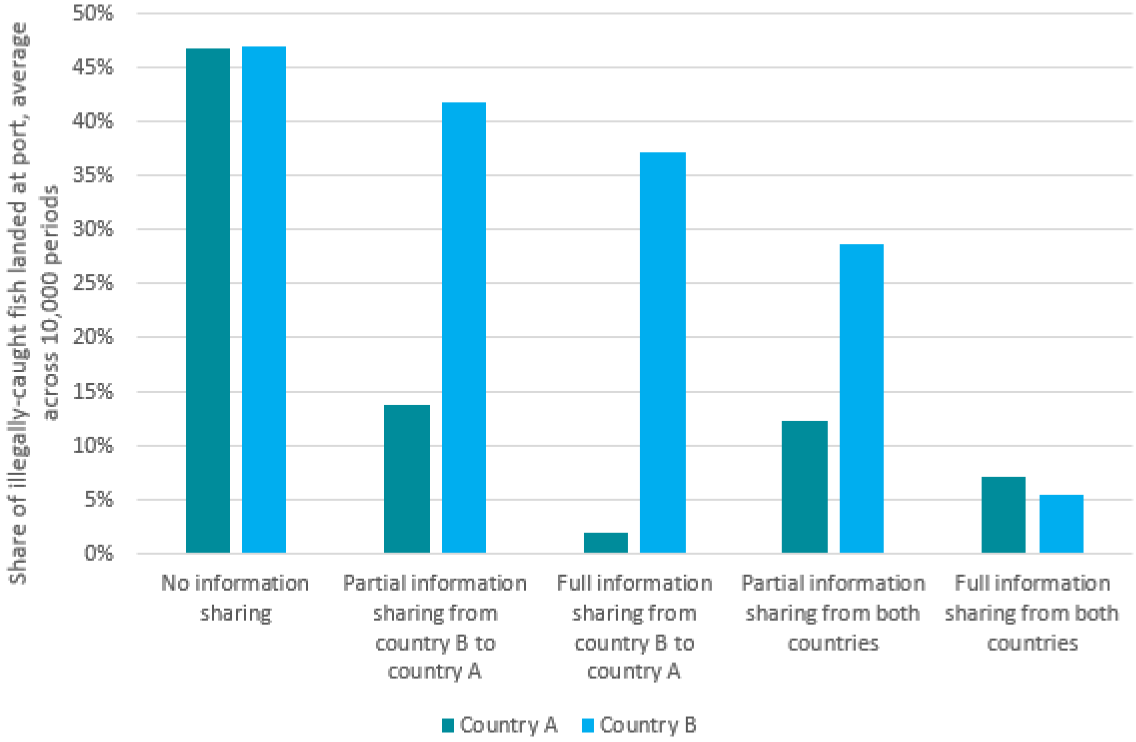


Figure 37 Share of fish caught illegally in country B, scenarios F – J



The effect of information sharing on the share of illegally caught-fish landed at the port in the high enforcement country (country B) is similar in the scenarios with heterogeneous enforcement structures to that observed in the equivalent homogeneous scenarios. The exception to this is scenario I (with partial information sharing by both countries), where the average share of illegally-caught fish landed at port B is 29%, compared to just 7% in scenario D. This reflects the more widespread occurrence of IUU fishing activities in country A's waters in scenario I relative to scenario E, which leads to significant volumes of illegally-caught fish being landed at the port in country B. In one sense, this can be viewed as a positive externality for the port in country B, since the increased traffic will boost revenues both through the potential imposition of fines as well as through any fees that are charged to incoming vessels. The share of illegally-caught fish landed at the port in country A is marginally higher in scenarios F – J than in the equivalent scenarios with homogeneous enforcement structures. This reflects the increased prevalence of IUU fishing activities brought about by the reduction in the number of enforcement agents in country A's waters.

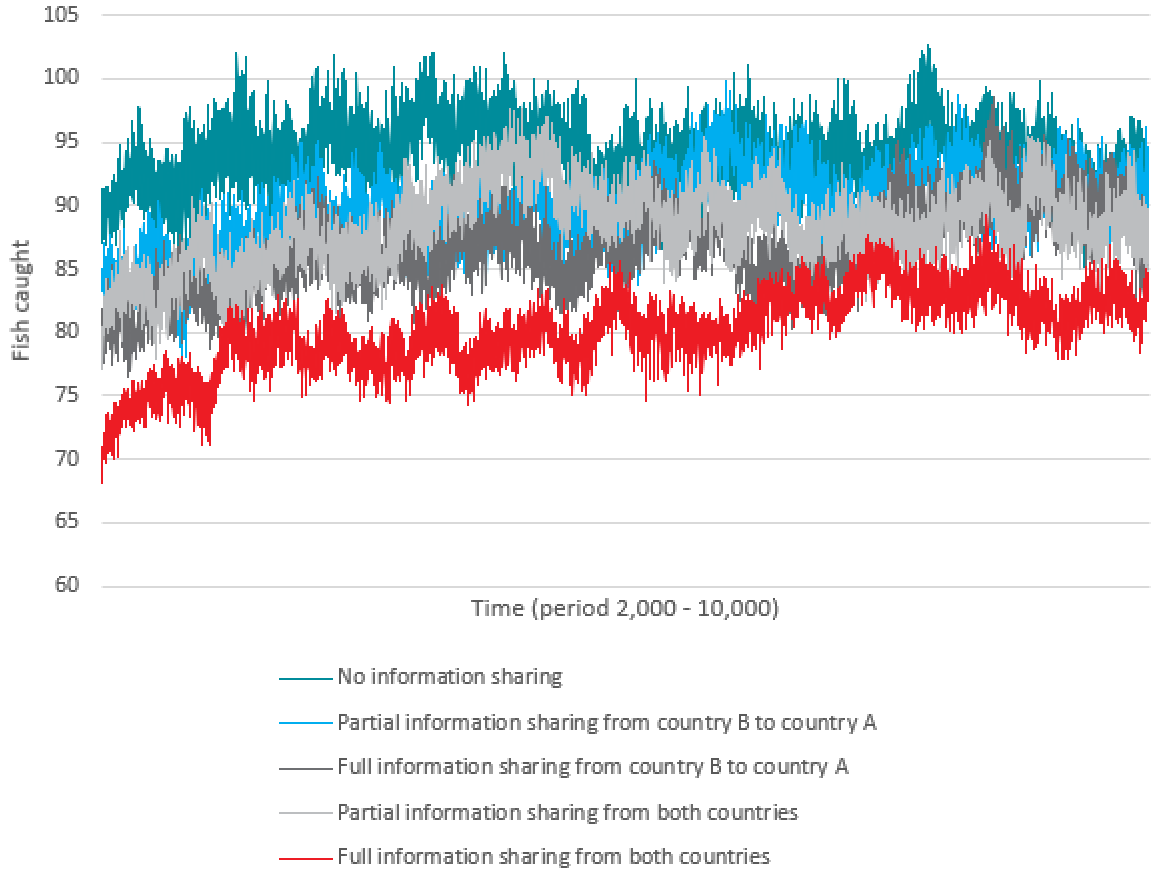
Figure 38 Share of illegally-caught fish landed at ports, scenarios F - J



Fishery yield

After 2,000 periods, the total amount of fish caught by the fishing fleet differs significantly between scenarios F and J, with relatively little variation between the intermediate cases (scenarios G – I). Over time, the average catch converges across the different scenarios. The average amount of fish caught by the fishing fleet in the final period is 89 in scenario F (with no information sharing) compared to 83 in scenario J (with full information sharing from both countries). This difference is significantly smaller than is the case in the equivalent scenarios with homogenous enforcement regimes (scenarios A and E). This is because, in the scenarios where country A has lowered the number of enforcement agents, a sizeable portion of fish are caught illegally, even when there is full information sharing from both countries. Since the optimal catch size is higher for fishing vessels engaging in IUU activities, this leads to a higher fishery yield.

Figure 39 Fish caught during period, scenarios F – J



The average quantity of fish caught each period by legal and illegal means in scenarios F – H is similar to the levels recorded in the equivalent scenarios with homogeneous enforcement frameworks (scenarios A – C). However, in scenario I – where enforcement agents in both countries share half of their detection information with the port authority in the neighbouring country – the legal fishery yield settles at around 65 units on average towards the end of the 10,000 period simulations. This compares to an average of around 75 units in scenario D. Furthermore, the quantity of fish caught legally per period is around 3 units lower in scenario J than it is in the equivalent scenario with homogeneous enforcement frameworks (scenario E). Meanwhile, the quantity of fish caught by illegal means each period averages around 23 units in the long run in scenario J, compared to less than 1 in scenario E. These results highlight that – even in cases of full information sharing by both countries – IUU activities can persist in circumstances where one country has relatively low enforcement standards.

Figure 40 Fish caught legally during period, scenarios F - J

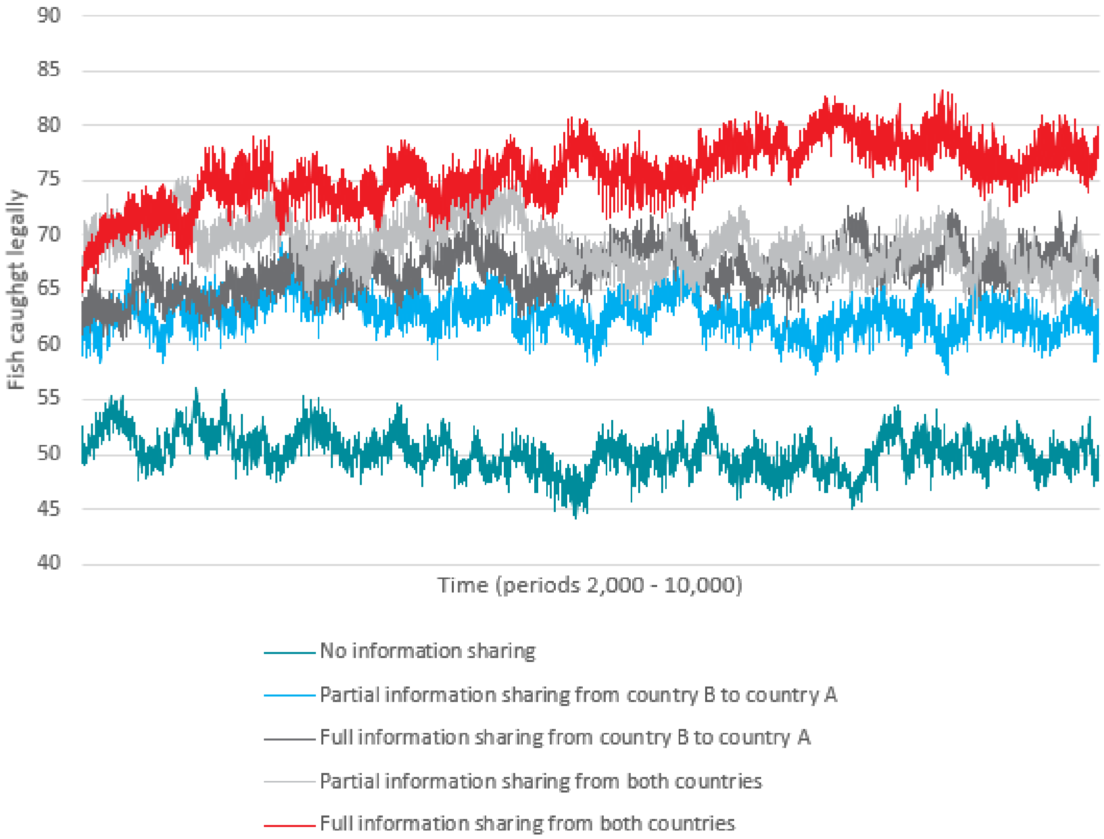
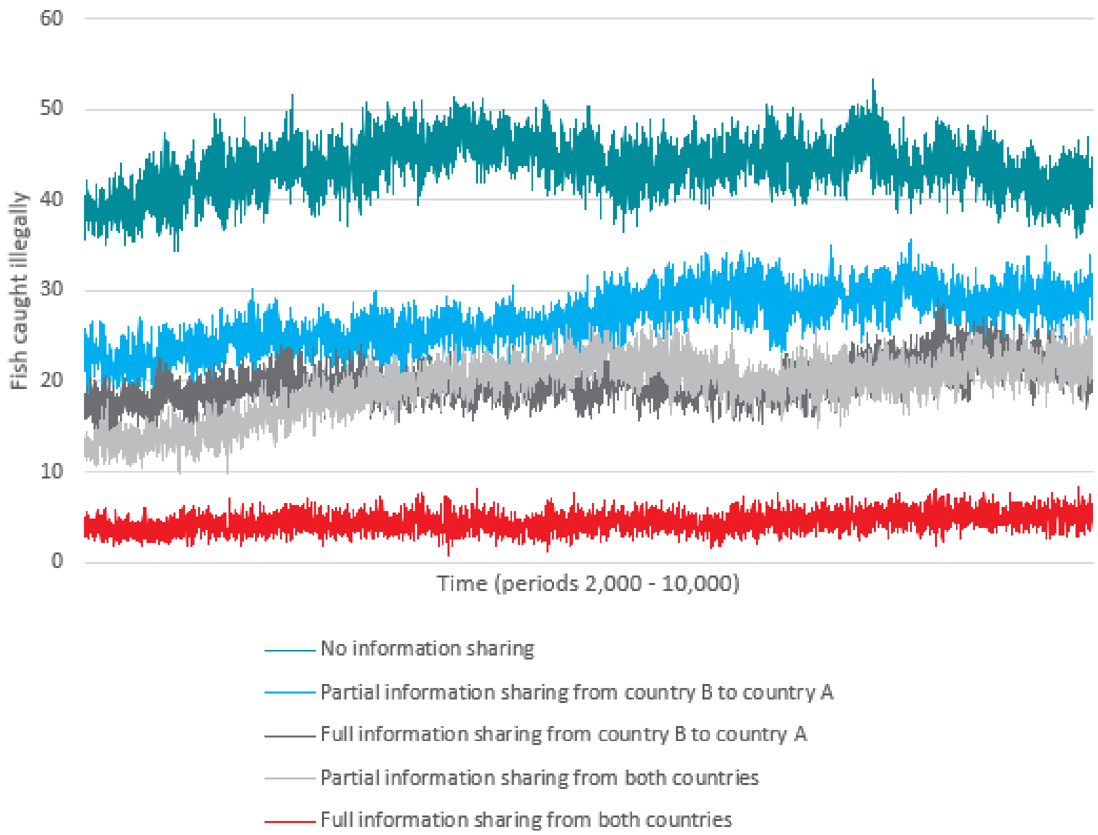


Figure 41 Fish caught illegally during period, scenarios F - J



The cumulative fishery yield is lower on average after 10,000 periods in scenarios with more information sharing, in the case of heterogeneous enforcement regimes. In scenarios G and H (where there is a one-way flow of information from country B to country A), the cumulative fishery yield is similar to the equivalent scenarios where the countries have identical regulatory environments. However, a gap emerges between the homogeneous and heterogeneous enforcement cases when country A begins to share information with country B. Indeed, in scenario I (where both countries share half of their information with each other), the cumulative fishery yield averages 893,956 after 10,000 periods. This is 8% higher than in scenario D. Meanwhile, the cumulative fishery yield is 4% higher on average after 10,000 periods in scenario J (with full information sharing between both countries) than in the equivalent scenario with homogenous enforcement regimes (scenario E). This can be explained by the fact that when both countries have a relatively high level of enforcement (scenarios A – E), full information sharing eventually largely eliminates illegal fishing activities. When country A lowers its enforcement standards (by halving the number of enforcement agents from 10 to 5), a certain degree of IUU fishing lingers on even in the case of full information sharing. This is because, fishing vessels with a low aversion to IUU activities still choose to operate illegally in country A's waters before landing their catch in country A's port, given the lower risk of detection precipitated by the reduction in the number of enforcement agents.

Table 17 Cumulative fishery yield after 10,000 periods, scenarios F - J

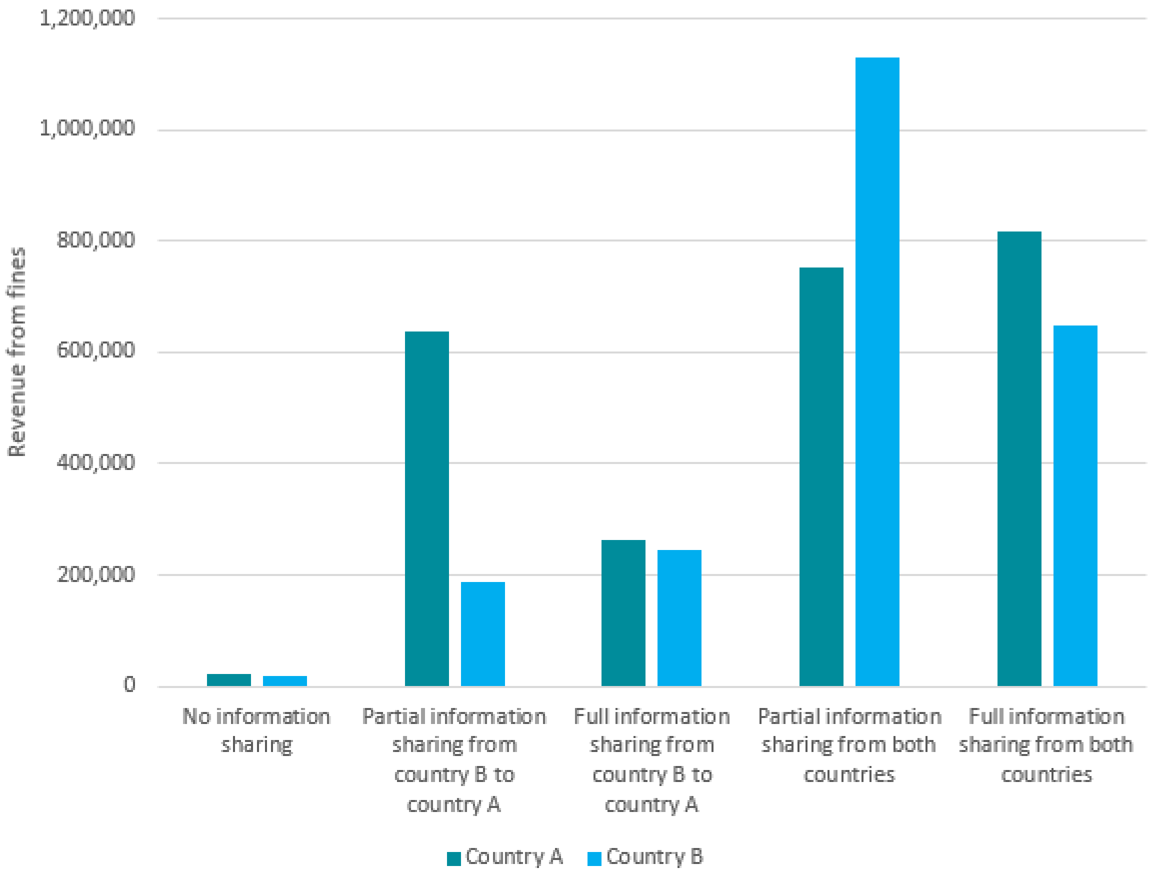
	Fishing yield after 10,000 periods	Legal fishing yield after 10,000 periods	IUU fishing yield after 10,000 periods
Scenario F	965,487	544,823	420,664
Scenario G	917,980	663,923	254,057
Scenario H	891,682	696,002	195,680
Scenario I	893,956	723,103	170,853
Scenario J	822,857	780,014	42,843

Revenue from fines for IUU activity

Reducing the number of enforcement agents in country A from 10 to 5 has significant ramifications on the revenues received from the fines imposed on fishing vessels that are found to have conducted IUU activities. In the case of full information sharing by both countries (scenario J), the average revenues from fines accumulated by country A is on average 354,770 units higher after 10,000 periods than in the equivalent case with homogeneous enforcement frameworks (scenario E). This is because, the lower levels of enforcement in country A mean that a significant level of IUU activity persists in all of the scenarios. In the case of full information sharing by both countries, fishing vessels that conduct IUU operations in country A's waters typically land their catch at the port in country A, leading to an ongoing stream of revenues from fines. This extent of this is far more limited when country A has 10 enforcement agents instead of 5, since fewer vessels are tempted to operate illegally.

In country B, the average revenue from fines accumulated during the 10,000 periods is 533,525 units higher in scenario I – with partial information sharing by both countries – than in scenario D. This is because, the lower enforcement standards in country A mean that more fishing vessels opt to carry out IUU activities in country A before landing their catch at the port in country B. This leads to a higher stream of revenues from fines for country B. As is the case with the scenarios with homogeneous enforcement frameworks, the total fine revenues across the two countries is typically highest in the case with partial information by both countries (scenario I).

Figure 42 Revenue from fines for IUU activities, scenarios F - J



5.3 Capacity constraints in low enforcement country (scenarios K – L)

The scenarios analysed thus far have assumed that the ports in both countries have the capacity to act upon any information they receive (either from their own enforcement agents or the neighbouring country's enforcement agents) and impose the appropriate fines on fishing vessels that are found to have conducted IUU activities. However, in reality, there is a panoply of reasons why ports may be constrained in their ability to conduct checks of suspected fishing vessels and impose sanctions where necessary. These include:

- **Technological barriers:** for information flows from enforcement agents to ports to be utilised effectively requires the recipient port to have the tools and knowhow available to receive, store, and interpret the incoming data. Many ports across the world still rely on paper-based systems, so progress is required to ensure that ports have the systems in place to process and act upon incoming information.[44]

44 World Economic Forum, 2019: Ending Illegal Fishing: Data Policy and the Port State Measures Agreement

- **Institutional barriers:** for sanctions to act as an effective deterrent, it is necessary that the relevant country has institutions in place that are able to enforce these sanctions when there has been a violation of the rules. There is a risk that in countries with weaker institutions, cases of corruption or fine evasion mean that even those fishing vessels that are detected at ports do not ultimately face the appropriate penalties.

- **Logistical / operational barriers:** the amount of traffic passing through ports can vary significantly, from the Port of Chimbote in Peru which receives more than 600,000 metric tonnes of fish each year to small scale ports that receive only a handful of landings each week.[45] Meanwhile, the resources available to inspect incoming fishing vessels and allocate fines also varies considerably between different ports. This variation in the volume of incoming traffic and the capacity to inspect it means that some ports simply do not have the resources necessary to act upon all of the information that they receive from enforcement agents.

Each of these barriers mean that there will be cases when fishing vessels that are detected conducting IUU activities will escape punishment, even if enforcement agents are able and willing to share the detection information with the relevant port.

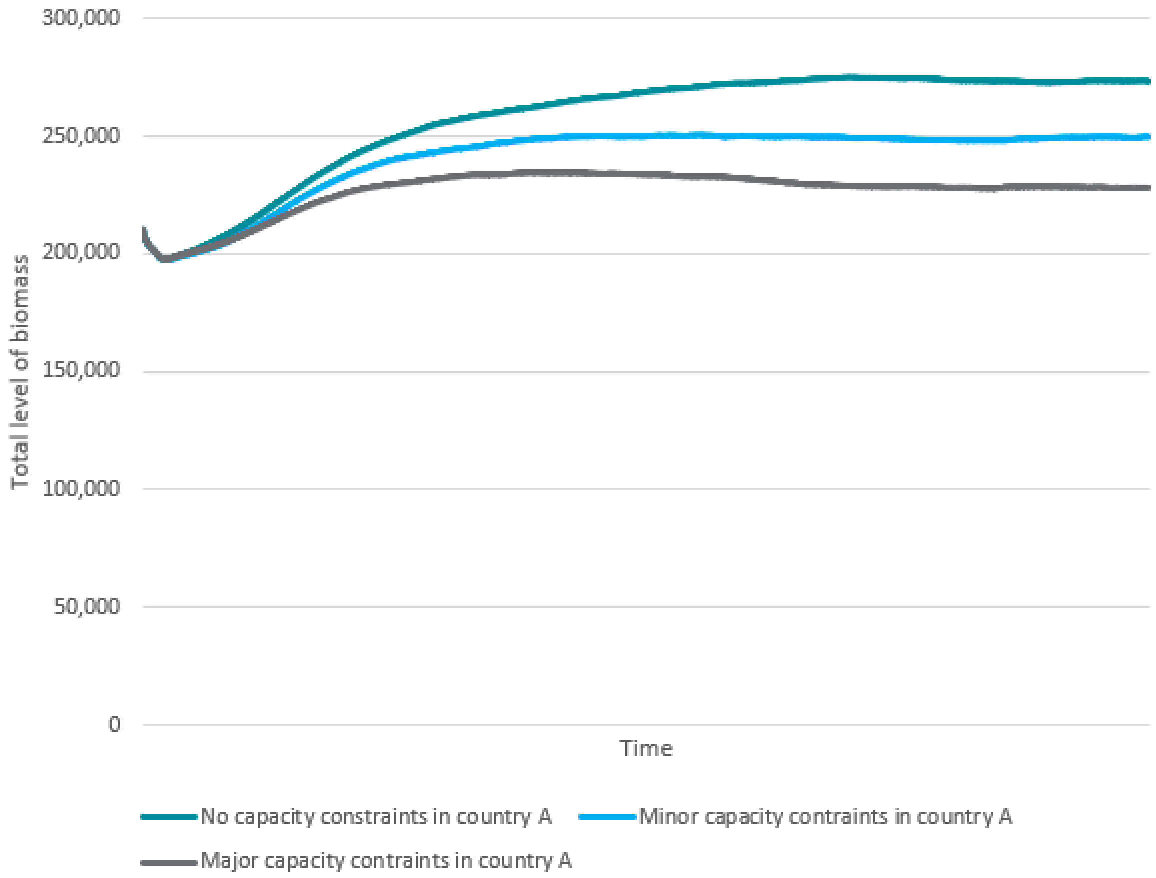
Scenario K examines the case where the low enforcement country (country A, which has 5 enforcement agents compared to country B's 10 enforcement agents) also has a minor capacity constraint at the port. The result of this capacity constraint is that for every four vessels that land at port A that the port has been told have acted illegally, only three will have the corresponding fine imposed upon them. Meanwhile, scenario L imposes a more significant capacity constraint on country A, whereby for every four vessels that land at port A that the port has been told have conducted IUU activities, only two will have the appropriate sanctions imposed. In scenarios K and L, the capacity constraints have been applied to the lower enforcement country because it is assumed that countries with fewer resources to patrol their waters are also more likely to suffer from the technological, logistical or institutional barriers that inhibit full enforcement at ports.

Total level of biomass

Capacity constraints at ports feed into the detection probabilities associated with IUU fishing activities. Figure 43 illustrates that – even when there is full information sharing by both countries – the introduction of capacity constraints has a considerable impact on the total level of biomass across the two countries. When country A transitions from having no capacity constraints (scenario J) to minor capacity constraints (scenario K), the total level of biomass after 10,000 periods averages 249,610 – a 9% fall compared to scenario J. There is an even more significant impact when country A moves from having minor capacity constraints to major capacity constraints. The total level of biomass after 10,000 periods in scenario L (with major capacity constraints) is 17% lower than in scenario J (with no capacity constraints).

45 The Pew Charitable Trusts, 2016: https://www.pewtrusts.org/en/research-and-analysis/articles/2016/01/05/new-analysis-identifies-worlds-largest-and-busiest-fishing-ports

Figure 43 Total level of biomass, scenarios J – L



Level of biomass in individual countries

In country A, the long run level of biomass in scenario K (with minor capacity constraints) is 12% lower than in scenario J (with no capacity constraints). Meanwhile, the average level of biomass in country A after 10,000 periods is just 107,345 in scenario L (with major capacity constraints) – more than 20% below the level in scenario J.

Turning to country B, there is a relatively small difference in the long run level of biomass between the case when there are minor capacity constraints in the port in country A (scenario K) and the case when there are no capacity constraints (scenario J). The more significant shift occurs when there are major capacity constraints in country A (scenario L). In this scenario, the average level of biomass in country B's waters after 10,000 periods is 120,575 – nearly 13% lower than in scenario J. Country B is affected by the capacity constraints in the port in country A because country A is now less able to impose sanctions on fishing vessels that conducted IUU activities in country B but landed their catch in country A. This reduces the risks associated with certain IUU fishing patterns in country B's territory, which in turn places pressure on the levels of biomass in that country.

The effects of the capacity constraints on biomass levels are more acute in country A. One factor driving this is that – in the context of full information sharing – a larger share of IUU activities are contained within a single country i.e. fishing vessels land their catch in the same country in which they fished it. This means that the port in country A's reduced capacity to impose penalties on IUU fishing vessels has a more direct impact on the incentives that fishing vessels face when operating in country A's waters. In country B, the probability of detection from carrying out IUU activities in country B and landing the catch in country B's port is unaffected by country A's capacity constraints.

Figure 44 Level of biomass in country A, scenarios J – L

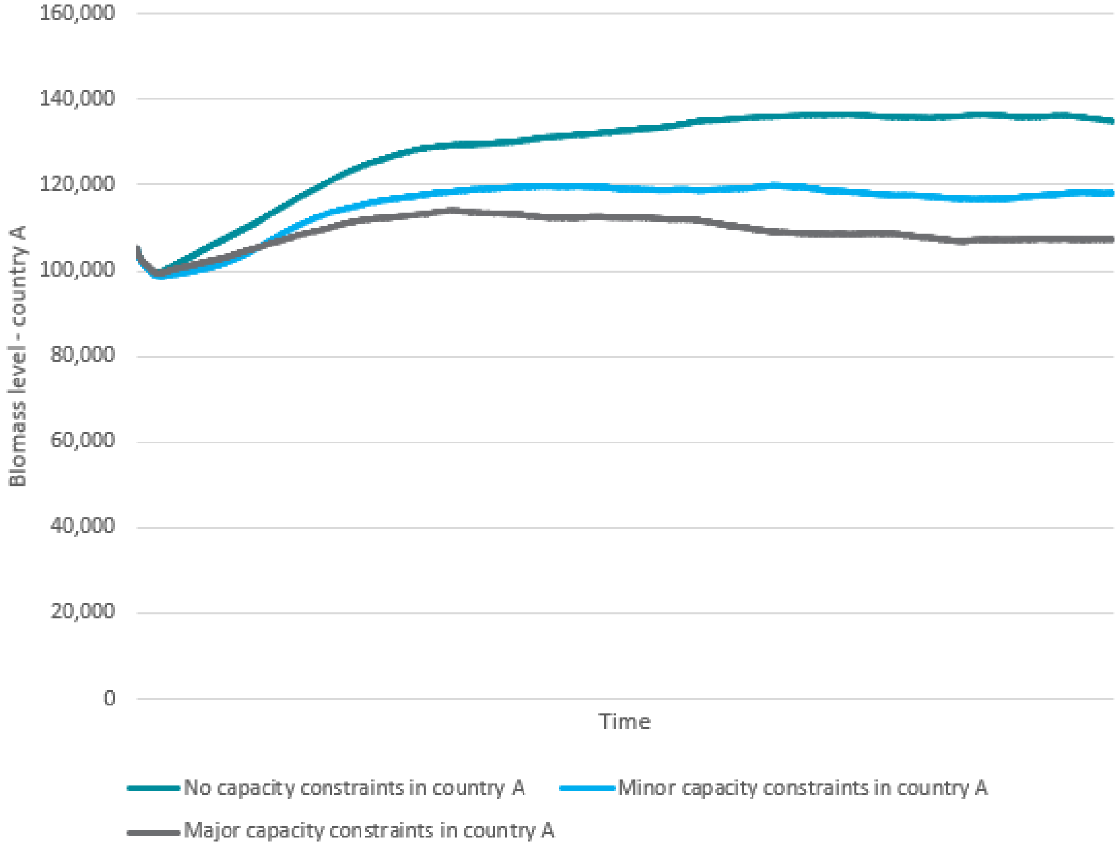
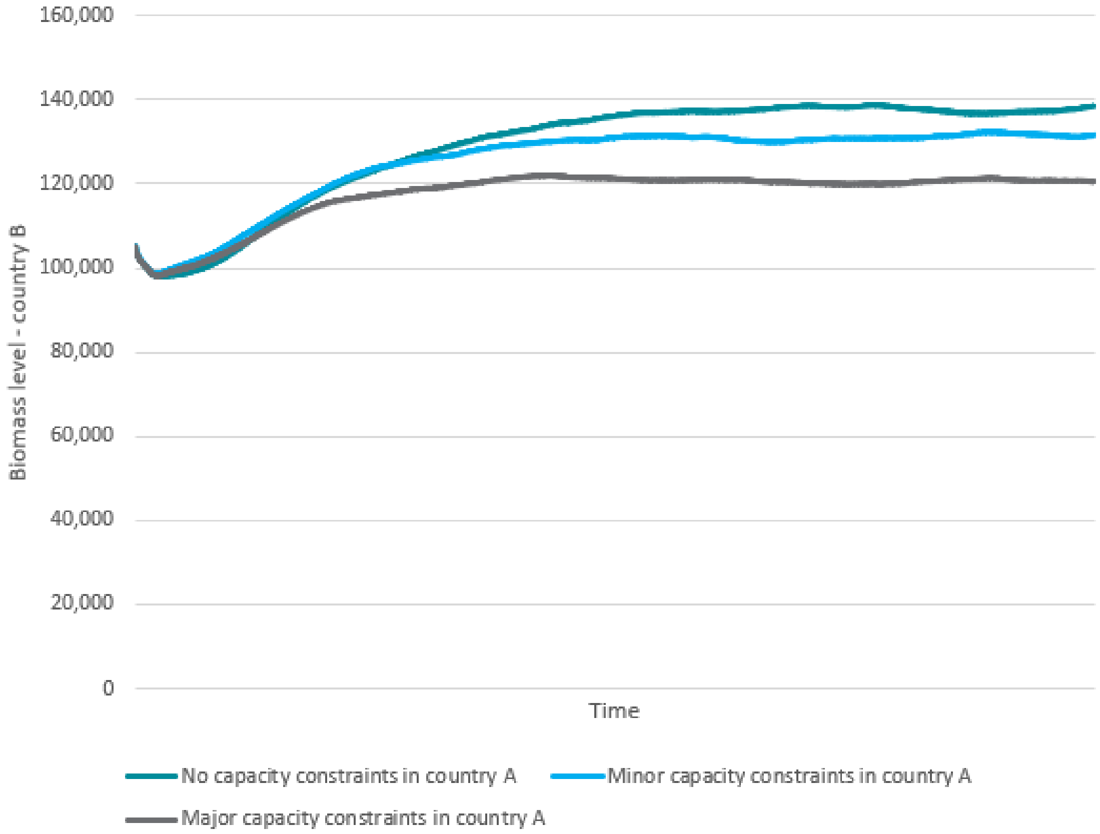


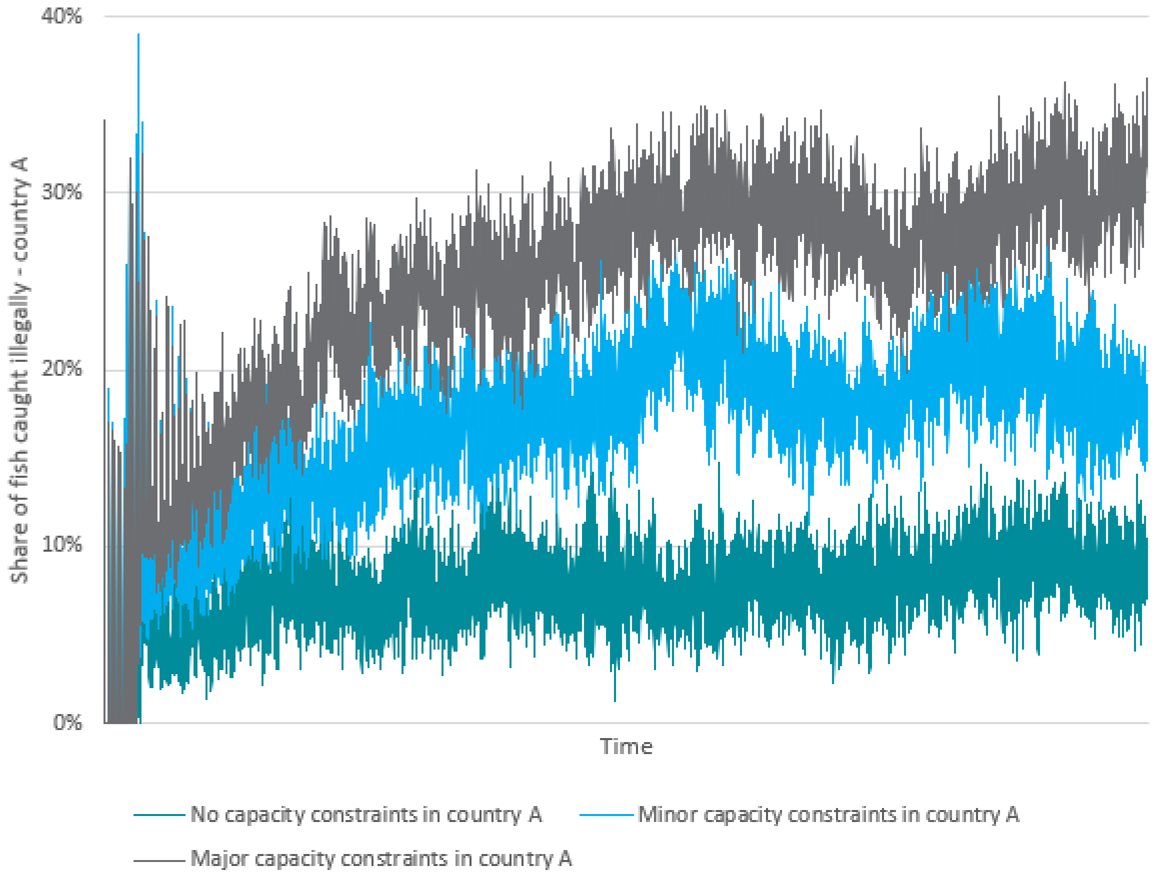
Figure 45 Level of biomass in country B, scenarios J – L



Prevalence of IUU activities

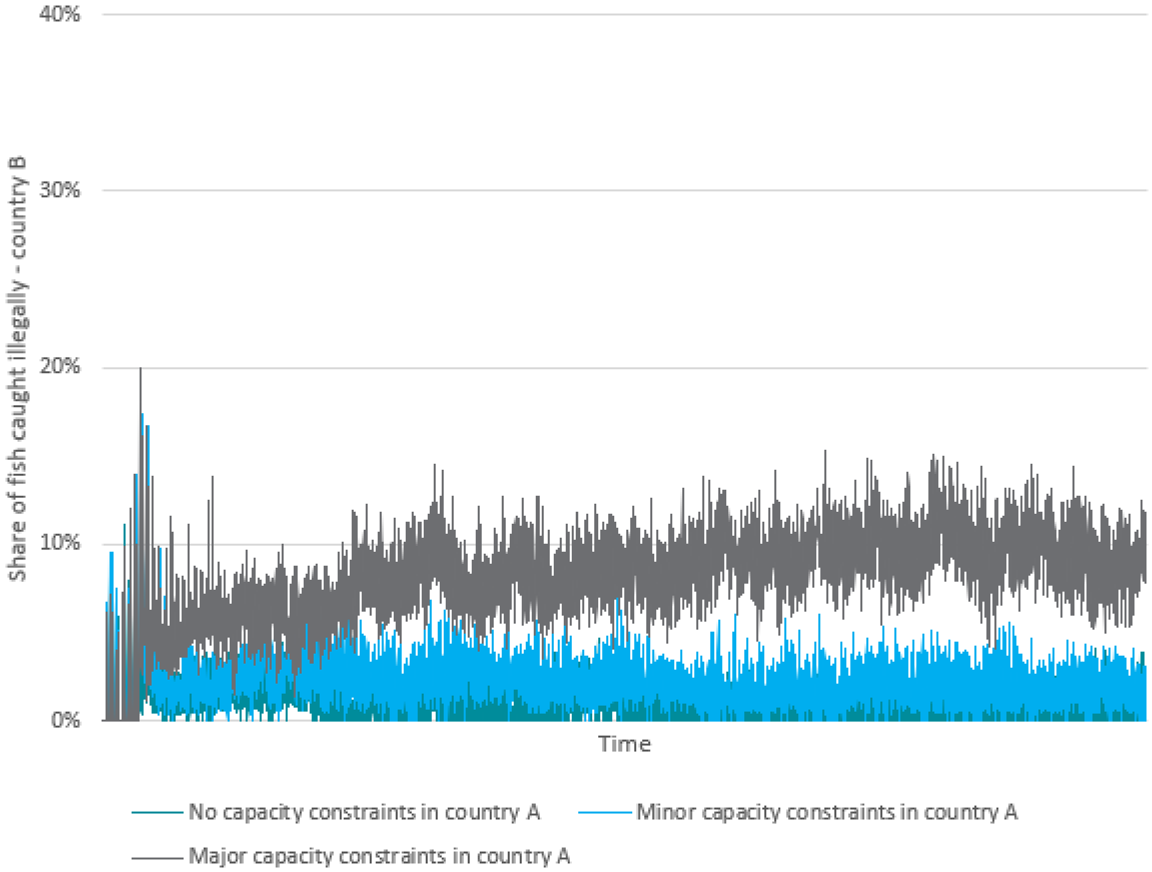
The capacity constraints faced by the port in country A and the corresponding reduction in sanctions imposed for IUU activities are conveyed to fishing vessels via the fall in observed detection probability. In scenario L (where country A has major capacity constraints), the share of fish caught illegally in country A's waters rises steadily during the early stages of the modelling simulations before hovering at just over 30%. This is around four times the share of fish that are caught illegally in the long-term in scenario J, when country A has an identical enforcement framework but no capacity constraints at the port.

Figure 46 Share of fish caught illegally in country A, scenarios J – L



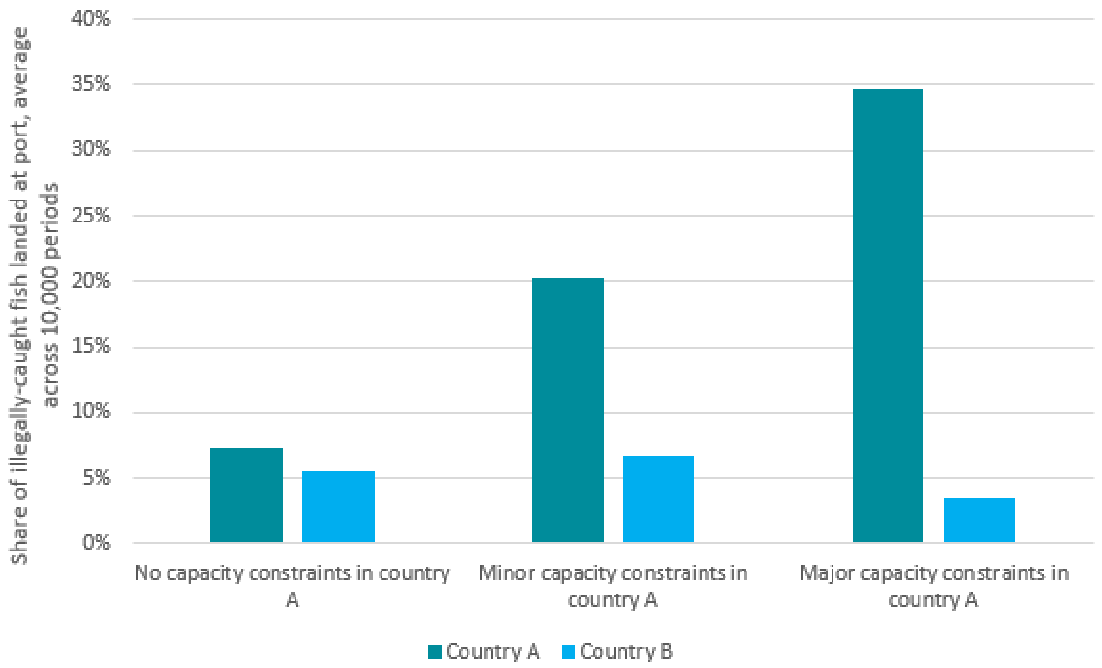
Meanwhile in country B, the share of fish that are caught illegally is around 10% on average towards the end of the simulations when there are major capacity constraints in the port in country A. The bulk of these acts will be cases where fishing vessels conduct IUU activities in country B's territory before returning to country A as a result of the capacity constraints which lower the risk of detection. There is a far more muted impact when there are only minor capacity constraints in the port in country A (scenario L), with around 2% of fish being caught illegally in country B's waters in later periods of the simulations.

Figure 47 Share of fish caught illegally in country B, scenarios J - L



Capacity constraints in country A do not have a significant impact on the share of illegally-caught fish landed at the port in country B. However, the average share of illegally-caught fish that are landed at the port in country A rises from just 7% in the case of no capacity constraints (scenario J) to 35% in the case of major capacity constraints (scenario L). The introduction of capacity constraints in country A makes it more attractive for fishing vessels to land their illegal catch at country A, regardless of the country in which it was caught. This is what drives the relatively one-sided impacts of capacity constraints on the share of illegally-caught fish landed at each port.

Figure 48 Share of illegally-caught fish landed at ports, scenarios J – L



Imposing capacity constraints on country A's ports means that for any fishing vessel that intends to land their catch at this port, the prospect of conducting IUU activities becomes more attractive relative to operating in a legal manner, due to a decreased risk of sanctioning. This is true for all fishing vessels, regardless of their individual aversion to IUU activities. Table 18 shows that – even in the case of full information sharing – the probability of being sanctioned after conducting IUU activities in country A's waters and landing the catch at the port in country A is just 13% when the port faces major capacity constraints (scenario L). This compares to 25% in scenario J where there are no capacity constraints. This dynamic is one of the key drivers of the increased cases of IUU activity presented above.

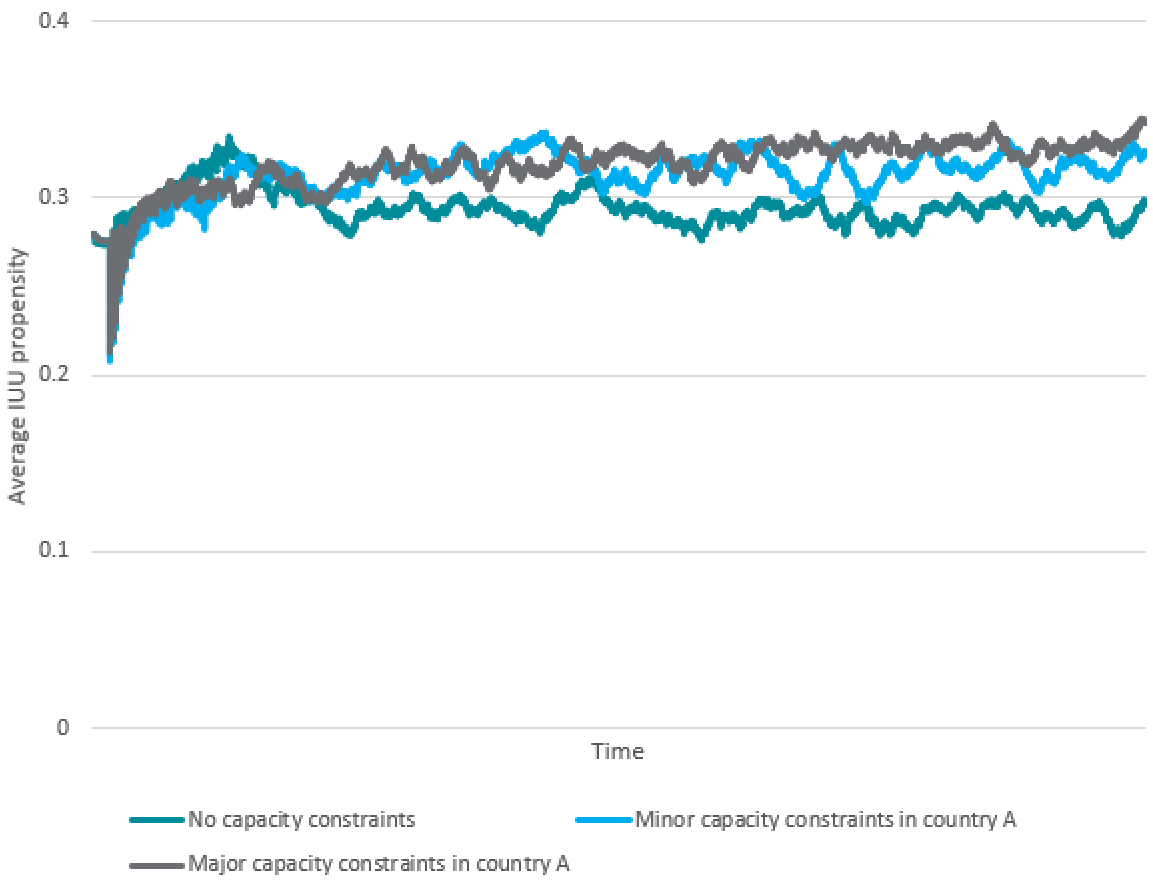
Table 18 Probability of being sanctioned associated with four fishing strategies, scenarios J - L

	Probability of being sanctioned after conducting IUU activities in country A's waters and landing catch at port in country A	Probability of being sanctioned after conducting IUU activities in country A's waters and landing catch at port in country B	Probability of being sanctioned after conducting IUU activities in country B's waters and landing catch at port in country A	Probability of being sanctioned after conducting IUU activities in country B's waters and landing catch at port in country B
Scenario J	25%	40%	50%	48%
Scenario K	16%	37%	45%	45%
Scenario L	13%	44%	31%	59%

Another driver, however, is a structural change in the composition of the fishing fleet. As was the case in conditions with weaker enforcement or limited information sharing, capacity constraints increase the profitability of fishing vessels with a higher propensity to commit IUU acts, since fines are imposed less frequently. As a result, these fishing vessels are more likely to remain in the market, which means that over time, the average characteristics of the fishing fleet as a whole shift. Indeed, the average value of the IUU-propensity coefficient is 0.34 in scenario L (with major capacity constraints), compared to 0.33 in scenario K (with minor capacity constraints) and 0.30 in scenario J (with no capacity constraints).

The average value of the IUU-propensity at various points in time during individual simulations is subject to a high degree of variability, since the value is randomly assigned to new vessels entering the market. The departure of specific vessels from the market can also create a step shift in the average value of the coefficient, particularly when the total number of active fishing vessels is relatively low. This variability means that there are periods in which the average value of the IUU-propensity coefficient is higher in scenarios with more effective enforcement frameworks. However, the overall trend points strongly to an increase in the average value of the coefficient when capacity constraints are introduced in the low enforcement country.

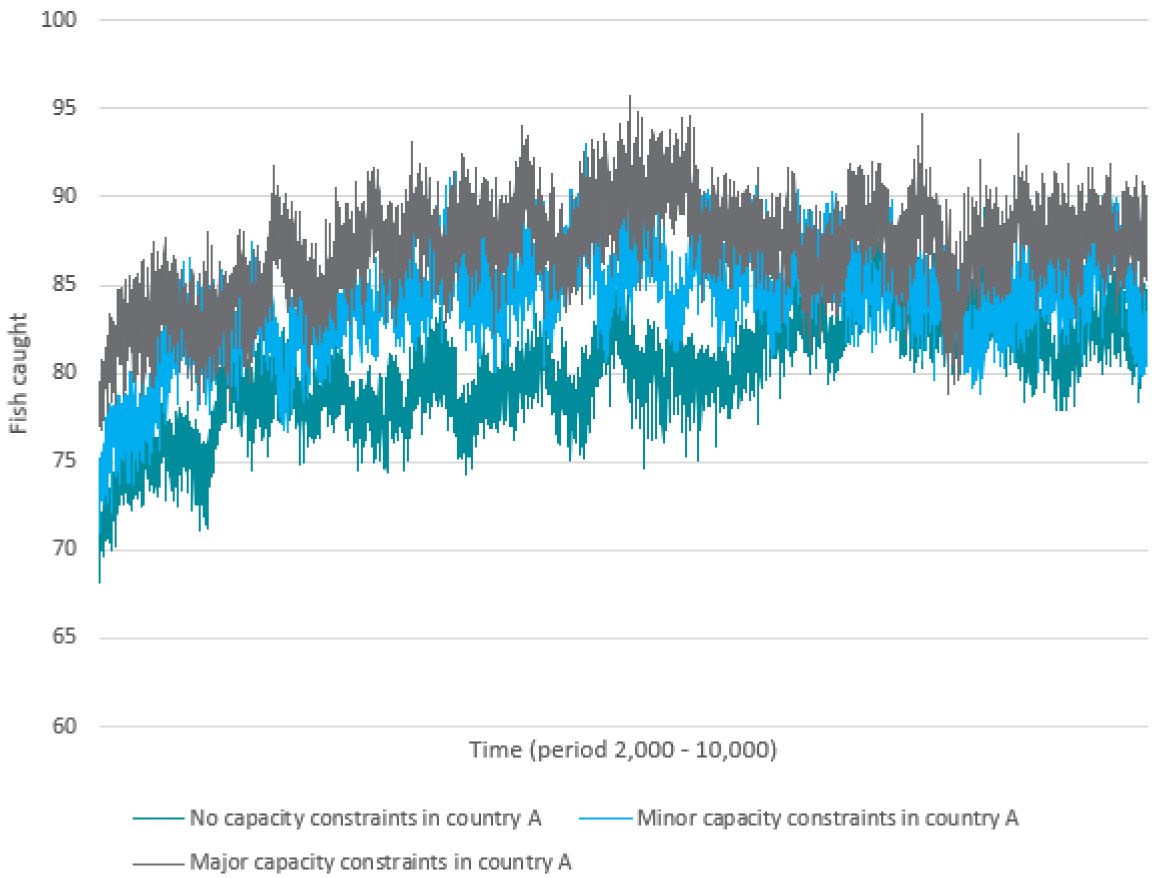
Figure 49 Average value of IUU-propensity coefficient, scenarios J - L



Fishery yield

A higher prevalence of IUU activity is associated with capacity constraints in country A. Given that IUU fishing vessels tend to catch a larger quantity of fish each period due to the lower cost curve, the total catch across the fishing fleet each period generally increases in line with the severity of the capacity constraints. In scenario J (with full information sharing and no capacity constraints), the fishing fleet on average catches around 82 units of biomass each period by the end of the modelling simulations. This is similar to the level recorded in scenario K (with minor capacity constraints in country A) but lower than the 88 units of biomass per period in scenario L (with major capacity constraints in country A).

Figure 50 Fish caught during period, scenarios J - L



The introduction of capacity constraints changes the composition of the total fishery catch each period. Indeed, Figure 51 shows that the quantity of fish caught each period tends to be higher in scenarios where there are minor (scenario K) or no (scenario J) capacity constraints at the port in country A. Meanwhile, the average illegal catch each period is typically around four times higher in scenario L – where the port authority in country A has major capacity constraints – than in scenario J, where there are no capacity constraints. This is because, the port authority's capacity constraints in country A create an environment that is more conducive to IUU activity, due to lower risks of fines being imposed at port even if fishing vessels are detected at sea.

Figure 51 Fish caught legally during period, scenarios J - L

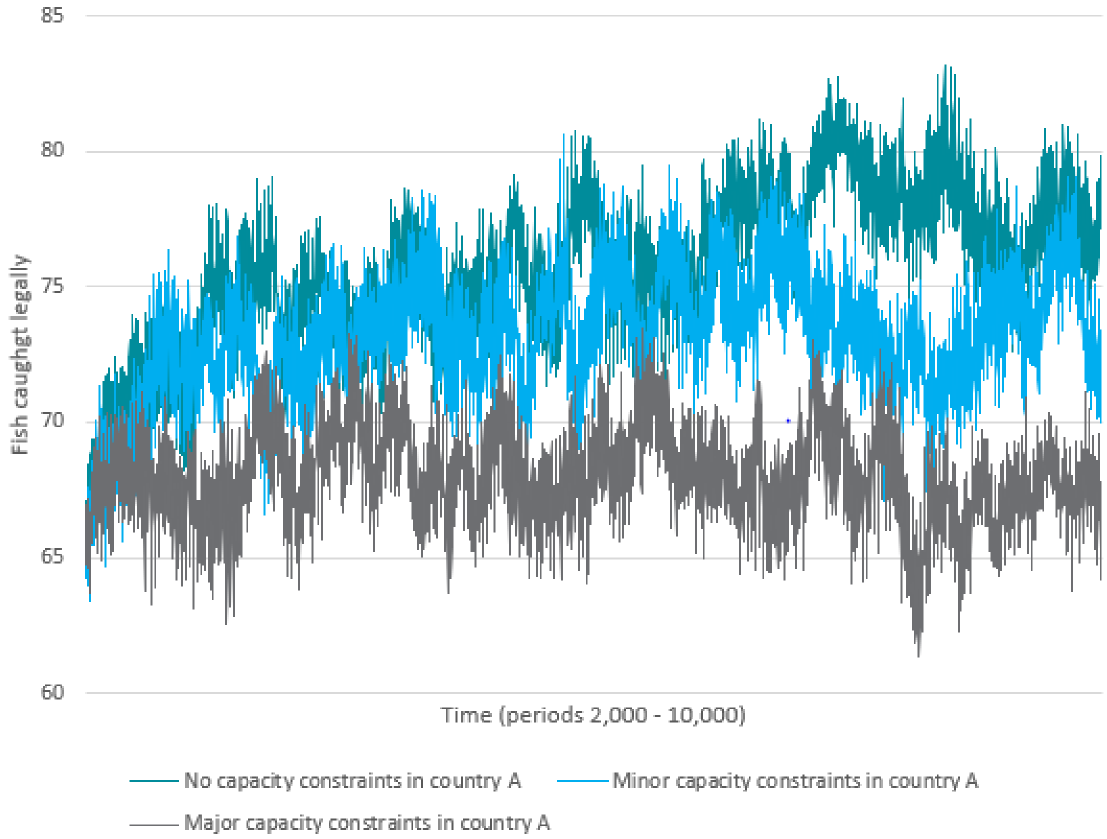
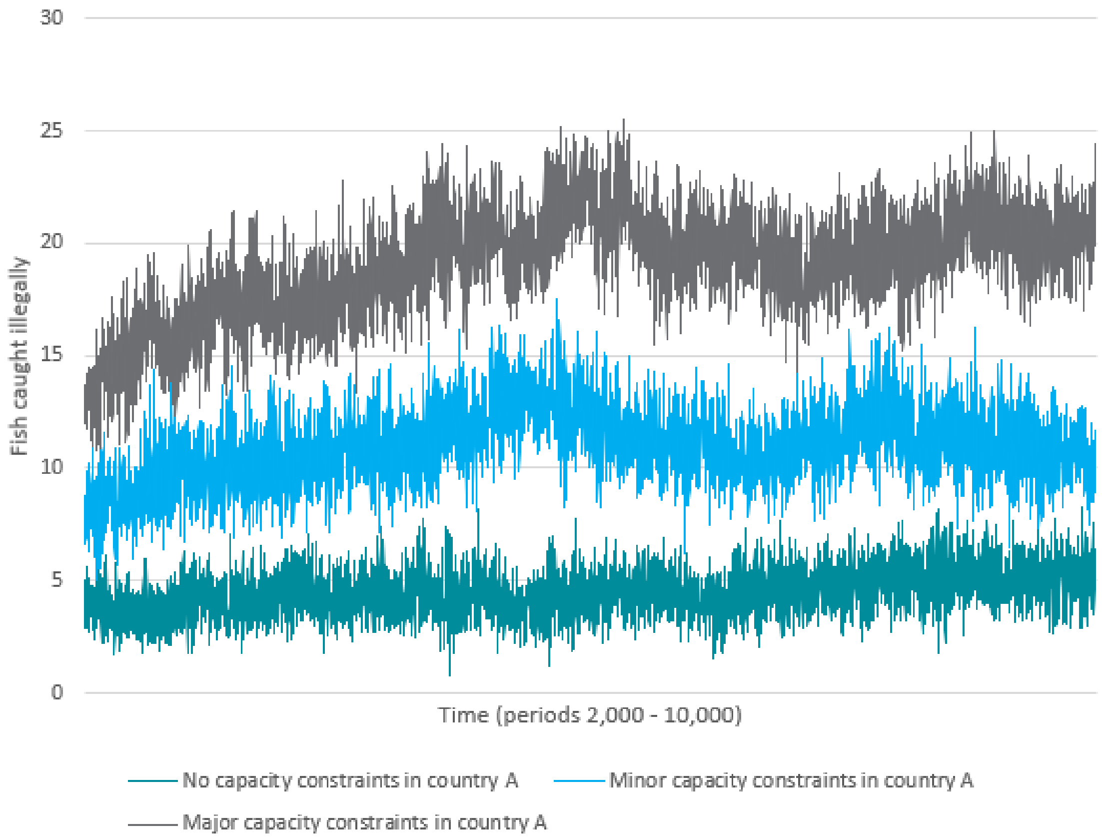


Figure 52 Fish caught illegally during period, scenarios J - L



The cumulative catch over the 10,000 period model simulations is higher on average in scenarios where there are capacity constraints in country A. Indeed, the cumulative catch averages 822,857 units in scenario J (with no capacity constraints) – 7% lower than in scenario L (with major capacity constraints). It is again interesting to note that the variation in the fishery yield in scenarios with differing levels of capacity constraints is considerably lower than the variation in other outcomes such as the prevalence of IUU fishing and the levels of biomass.

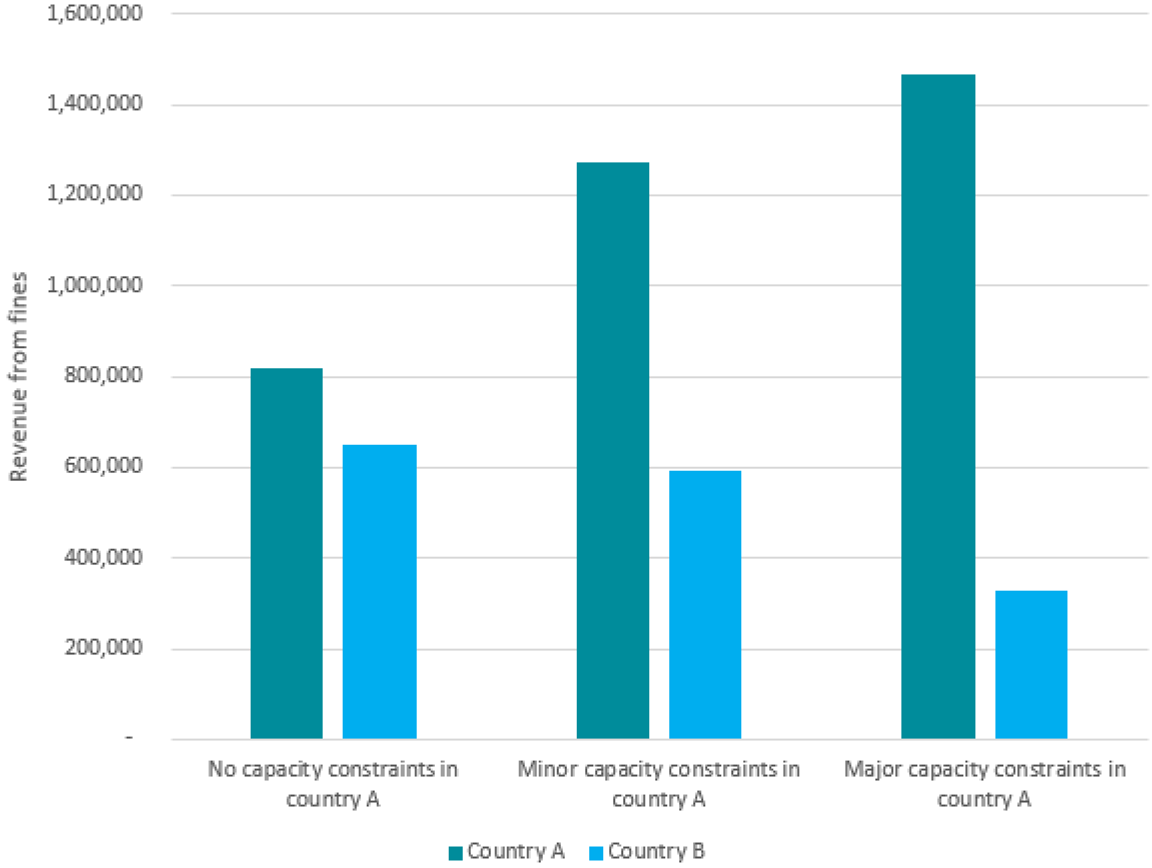
Table 19 Cumulative fishery yield after 10,000 periods, scenarios J - L

	Fishing yield after 10,000 periods	Legal fishing yield after 10,000 periods	IUU fishing yield after 10,000 periods
Scenario J	822,857	780,014	42,843
Scenario K	858,920	758,609	100,311
Scenario L	888,491	716,999	171,492

Revenue from fines for IUU activity

One of the leading causes of port authorities' capacity constraints is a lack of the resources necessary to carry out checks and sanctioning to the desired standard. The results of the modelling show that revenues from fines are maximised for in country A when it has major capacity constraints. While it is seemingly counter-intuitive that a fall in enforcement standards brings about an increase in revenues from fines, this can be explained by the high amount of IUU activity that persists when there are capacity constraints in country A. Even when the port authority in country A faces major capacity constraints, there are still a significant number of fishing vessels that are sanctioned. By contrast, in the absence of capacity constraints and with full information sharing, the amount of IUU activity is very low, leading to a reduced stream of revenues. This pattern can create an interesting dynamic in which additional revenues generated from fines as a result of capacity constraints can be used to address these capacity constraints. This in turn could lead to a decrease in the revenues from fines and a corresponding fall in the ability to manage capacity constraints, potentially triggering a return to the original conditions.

Figure 53 Revenue from fines for IUU activities, scenarios J - L



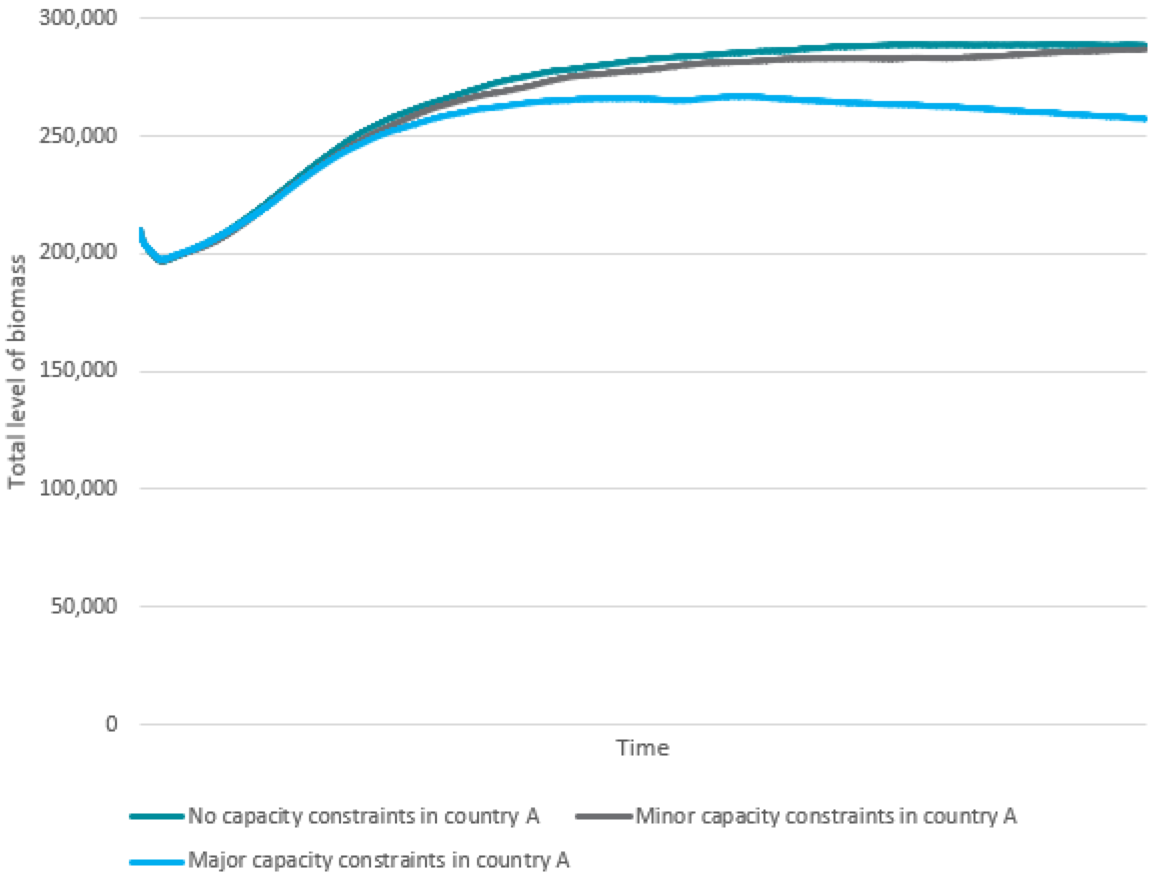
5.4 Capacity constraints in high enforcement country (scenarios M – N)

In order to isolate the impacts of capacity constraints at ports, scenarios M and N consider the effects of varying degrees of capacity constraints at the port authority in country A, where both countries have 10 enforcement agents and there is full information sharing by both countries. Scenario M considers the case of minor capacity constraints (where three out of every four vessels against which the port authority in country A has evidence to suggest operated illegally are sanctioned), and scenario N considers the case of major capacity constraints (where two out of every four vessels against which the port authority in country A has evidence to suggest operated illegally are sanctioned). The equivalent scenario without any capacity constraints is scenario E, which is used as a benchmark case.

Total level of biomass

Interestingly, the introduction of minor capacity constraints in country A (scenario M) has a very minimal effect on the total level of biomass across the two countries. This shows that in the context of full information sharing and a relatively high number of enforcement agents in both countries, the probabilities of detection of IUU activities are sufficiently high to discourage illegal operations, even when there is a chance of evading sanctioning at the port authority in country A. In scenario N – where country A has major capacity constraints – the average level of biomass after 10,000 periods is 257,321 – 11% lower than in the equivalent scenario with no capacity constraints (scenario E). This reduction is more significant than the 5% decline in the long-run level of biomass when the number of enforcement agents in country A is lowered from 10 (as in scenario E) to 5 (as in scenario J). This suggests that weak enforcement standards at a port in one country have a more deleterious impact on the health of the overall fishery than weak enforcement standards at sea in one country.

Figure 54 Total level of biomass, scenario E, scenario M and scenario N



Level of biomass in individual countries

Variations in the enforcement standards or practices of a single country have previously been found to have differential impacts on the levels of biomass in each country. For instance, the one-way sharing of information has a larger positive impact on the level of biomass in the country sharing the information, while a reduction in the number of enforcement agents has the most direct impact on the level of biomass in the country in which the change was made. However, in the case of capacity constraints in one country and otherwise homogeneous enforcement regimes, there is relatively uniform impact on the level of biomass in country A and country B. For both countries, the long-run level of biomass is largely unaffected by the introduction of minor capacity constraints in country A. Meanwhile, major capacity constraints in country A lead to an 11% fall in the long-run level of biomass in country A relative to scenario E, and a 10% reduction in country B.

Figure 55 Level of biomass in country A, scenario E, scenario M, scenario N

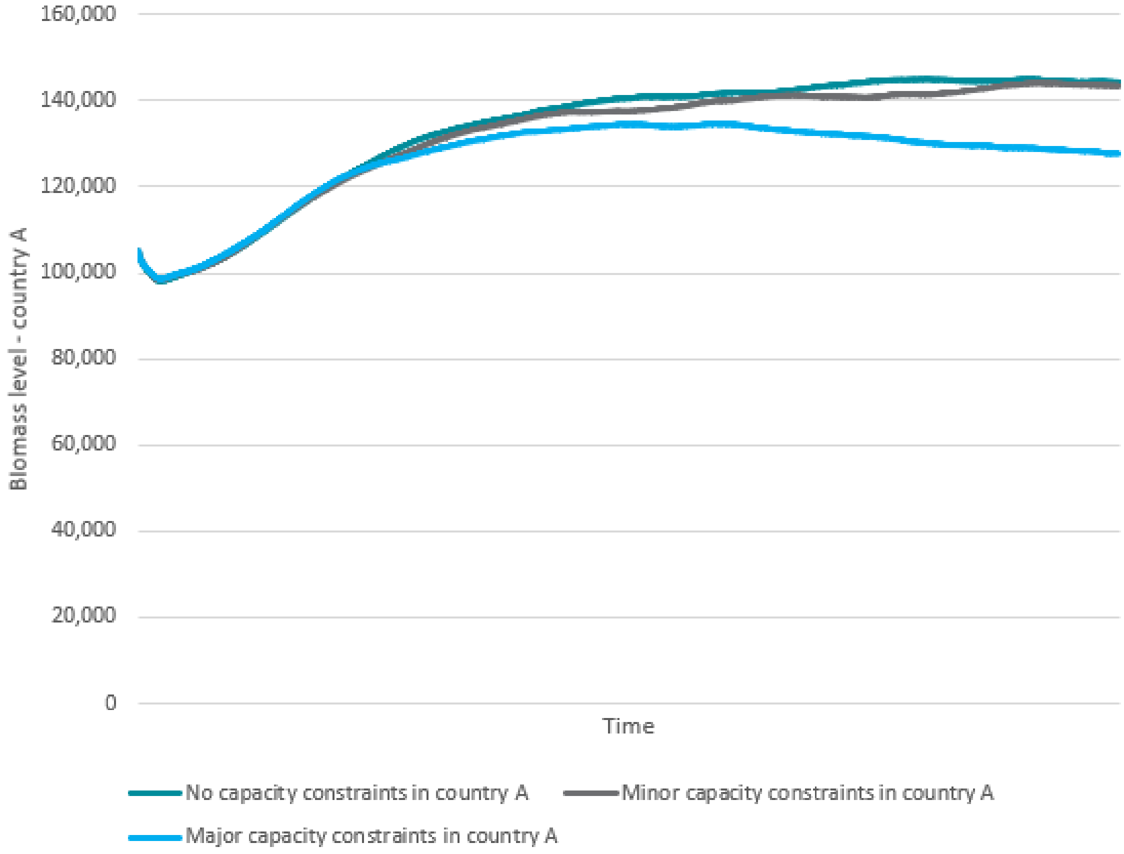
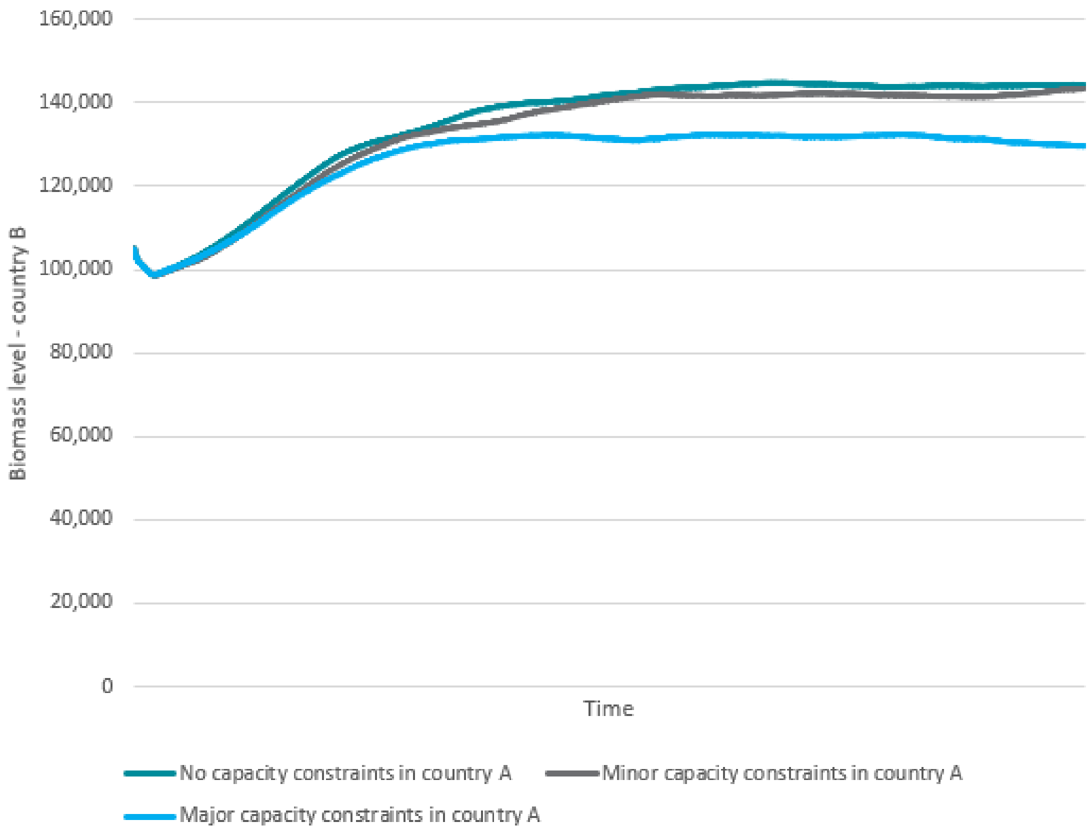


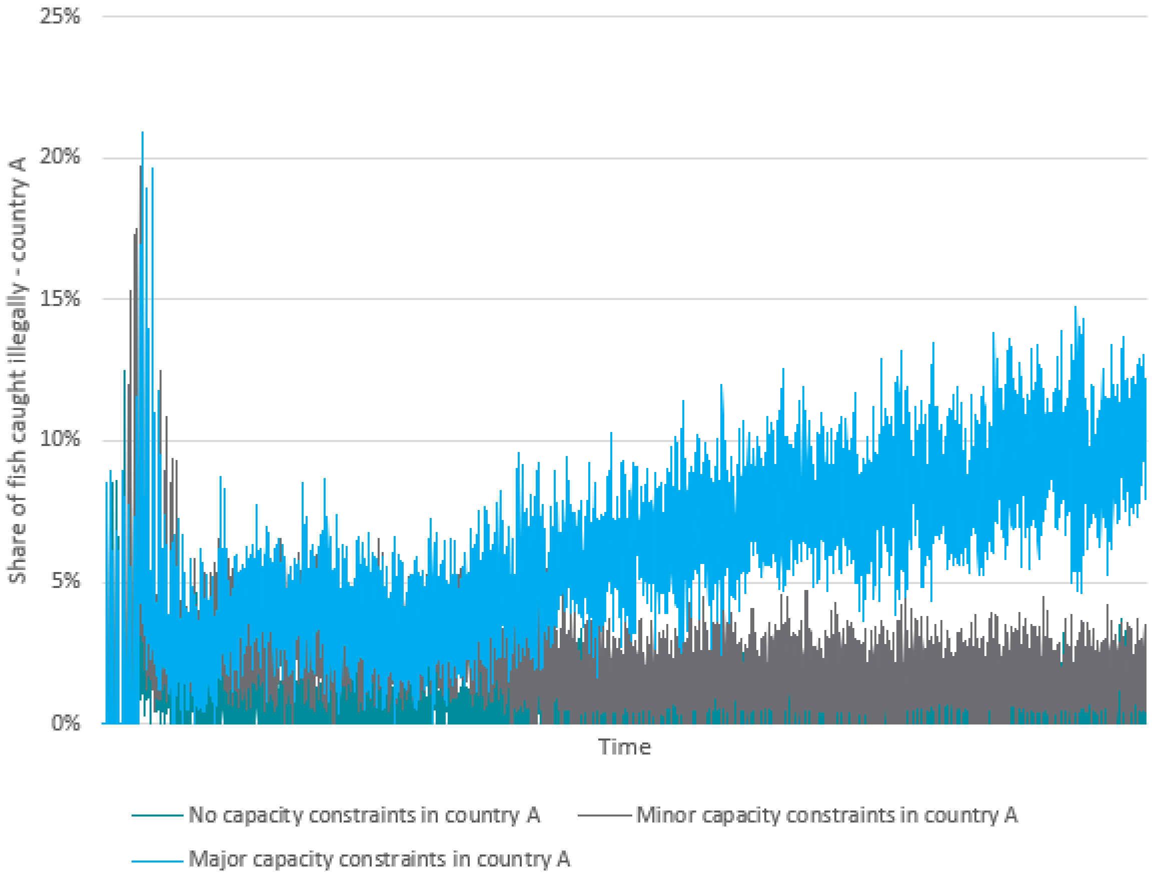
Figure 56 Level of biomass in country B, scenario E, scenario M, scenario N



Prevalence of IUU activities

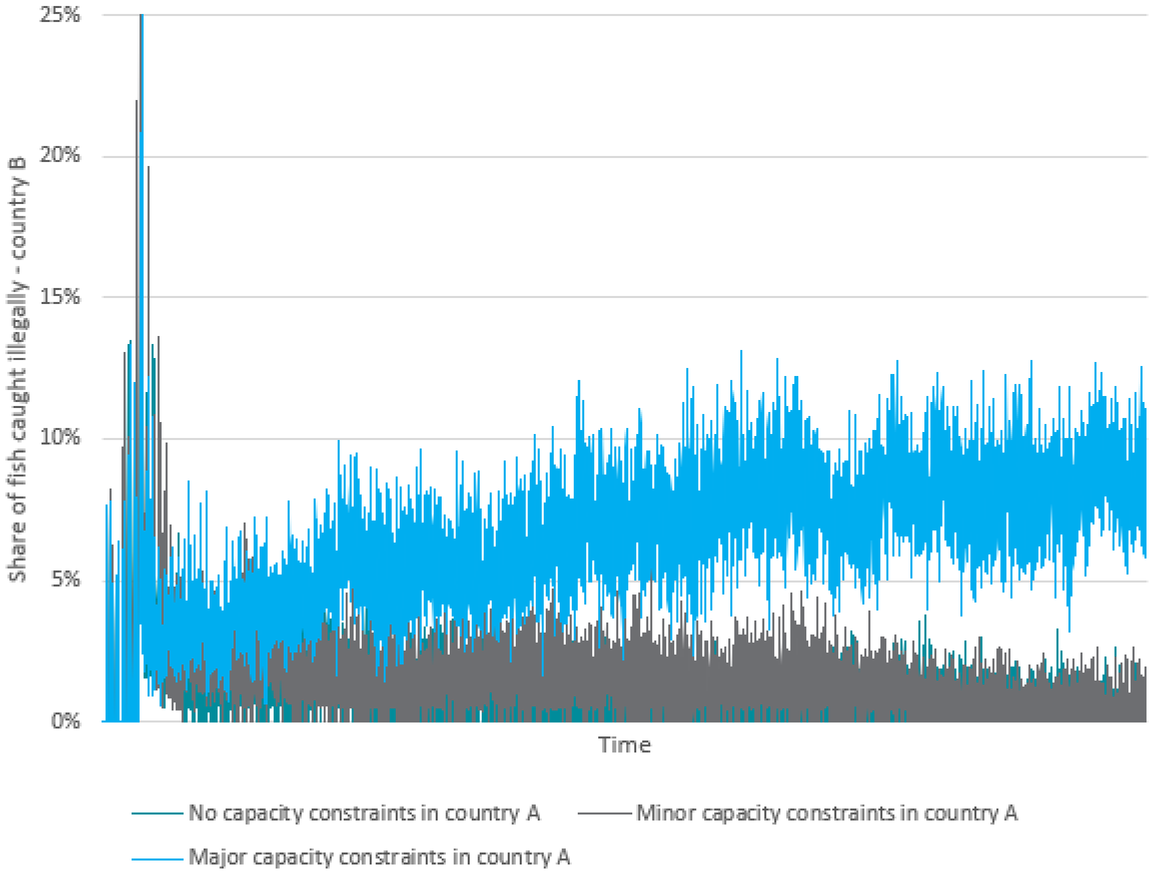
The introduction of minor capacity constraints at the port authority in country A creates a small increase in the amount of IUU activity taking place in country A. Towards the end of the 10,000 period simulations, the average share of fish that are caught illegally averages around 2%, compared to less than 1% in the absence of capacity constraints. There is a step change when major capacity constraints are introduced, with around 10% of fish caught illegally each period in country A's waters in the long run. This is slightly above the average share recorded in scenario J, where there are no capacity constraints and full information sharing but the number of enforcement agents patrolling country A's is 5 instead of 10. This finding again suggests that addressing major capacity constraints within port authorities can be the most effective way of deterring IUU fishing. Comparing the results across the various scenarios that have been analysed points to important interaction effects that are at play which shape the share of fish caught illegally. Indeed, the increase in the share of fish that are caught illegally in scenario L (where there are major capacity constraints in country A and 5 enforcement agents instead of 10) is far more significant than the combined rises associated with a reduction in the number of enforcement agents or an introduction of major capacity constraints in isolation. An implication of this finding is that a deterioration of enforcement standards across multiple dimensions can be far more detrimental to the health of the fishery system than a slipping of standards in individual areas.

Figure 57 Share of fish caught illegally in country A, scenario E, scenario M, scenario N



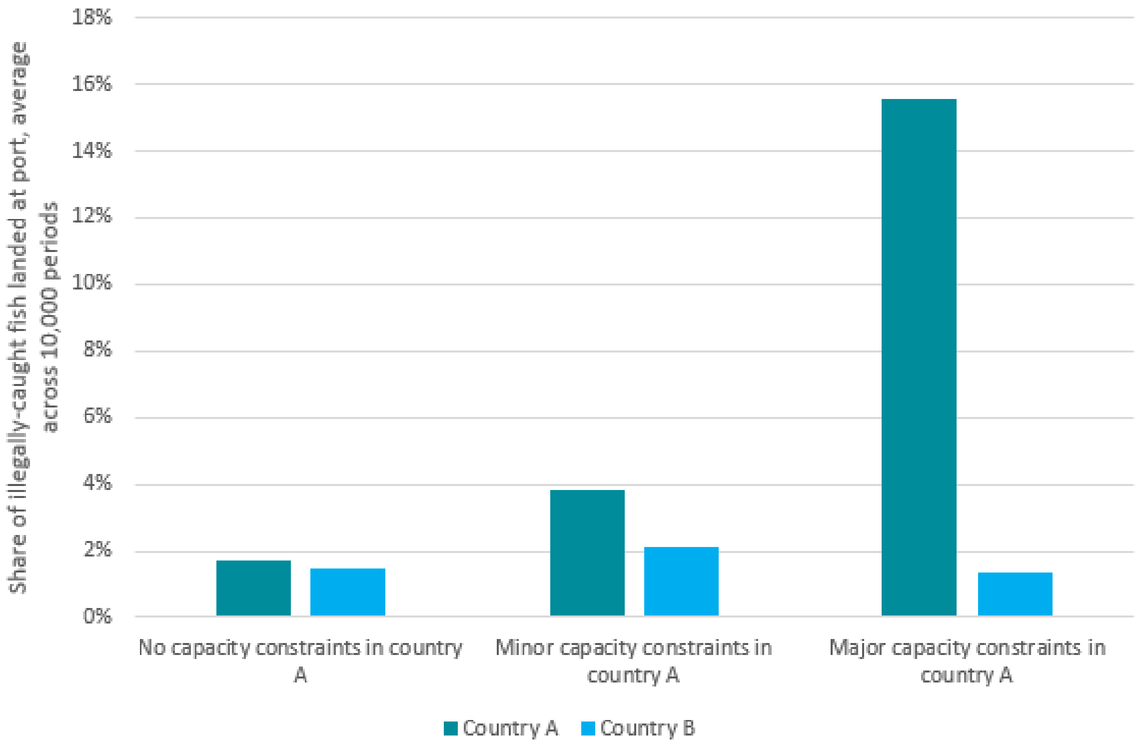
In country B, the share of fish caught illegally rises from less than 1% on average towards the end of the simulations in scenario E (with no capacity constraints) to around 1% in scenario M (with minor capacity constraints in country A) and 9% in scenario N (with major capacity constraints). These results again highlight that in the case of otherwise homogeneous enforcement regimes, the introduction of capacity constraints in one country has a fairly uniform effect on both countries. This is because, major capacity constraints at the port authority in country A make it more attractive for fishing vessels to conduct IUU operations in country B's waters before crossing the border to land their catch in country A.

Figure 58 Share of fish caught illegally in country B, scenario E, scenario M, scenario N



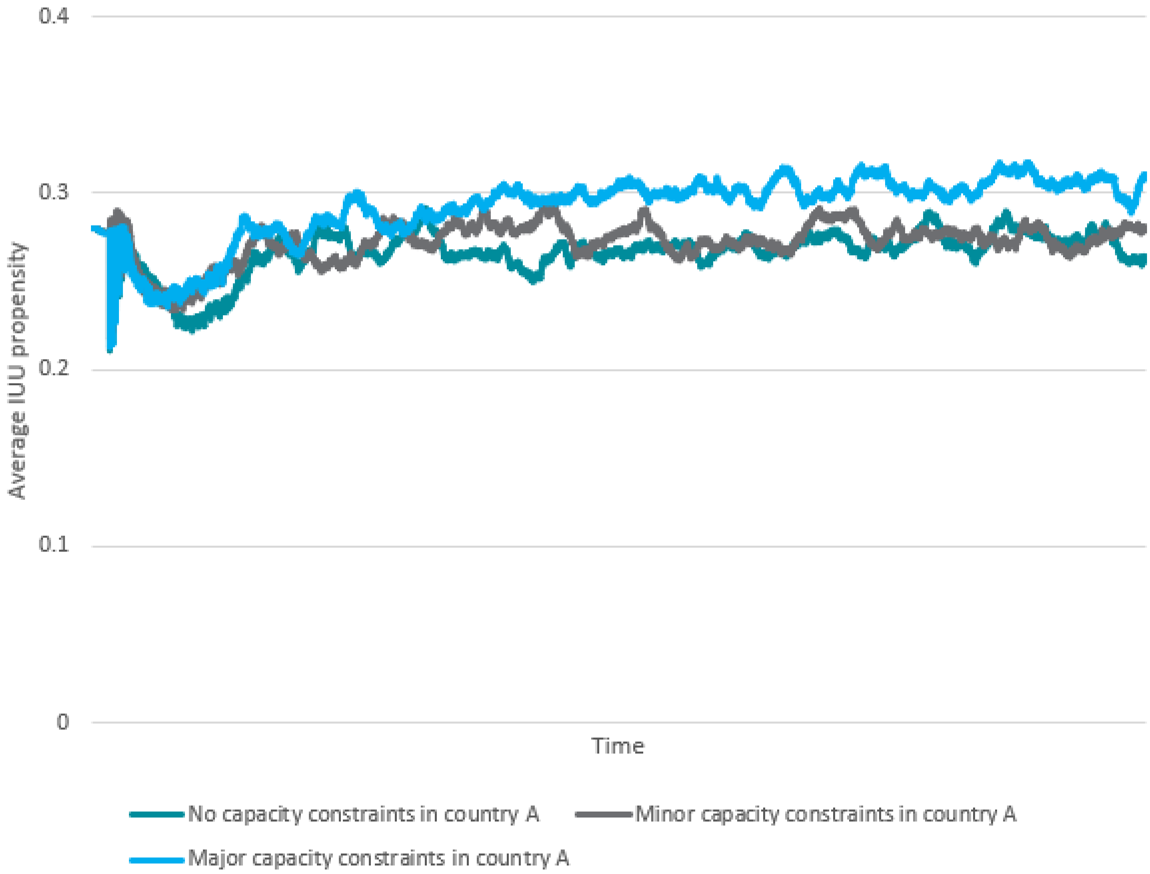
The transition from minor capacity constraints in country A to major capacity constraints is accompanied by a significant increase in the levels of IUU fishing activity taking place, in both countries. As a result of this, there is also a considerable increase in the share of illegally-caught fish landed at the port in country A between scenario M (with minor capacity constraints) and scenario N (with major capacity constraints). There is less of an impact on this metric for country B, since in the presence of major capacity constraints at country A, most fishing vessels with illegal catch will opt to land at the port in country A. The share of illegally-caught fish landed at both ports is lower in scenarios M and N than they are in the equivalent scenarios where country A also has fewer enforcement agents (scenarios K and L, respectively). This reflects the reduced prevalence of IUU activity as a result of the increased enforcement capabilities in country A's waters.

Figure 59 Share of illegally-caught fish landed at ports, scenario E, scenario M, scenario N



As has been observed when varying other enforcement parameters, the introduction of capacity constraints in one country leads to a structural shift in the collective characteristics of the fishing fleet. After 10,000 periods, the average value of the IUU-propensity coefficient is 0.31 in scenario N, compared to 0.26 in scenario E (where there are no capacity constraints).

Figure 60 Average value of IUU-propensity coefficient, scenario E, scenario M, scenario N



The structural change in the characteristics of the fishing fleet is one of the factors leading to a higher prevalence of IUU fishing in scenarios where there are major capacity constraints at the port authorities in country A. The other key factor is the change in the probability of being sanctioned after conducting IUU activities, which affects the decision-making of all fishing vessels, regardless of the value of their IUU-propensity coefficient. Table 20 shows that the introduction of major capacity constraints causes a systematic decrease in the probability of being sanctioned upon returning to port A after having conducted IUU activities, either in country A's waters or country B's waters.

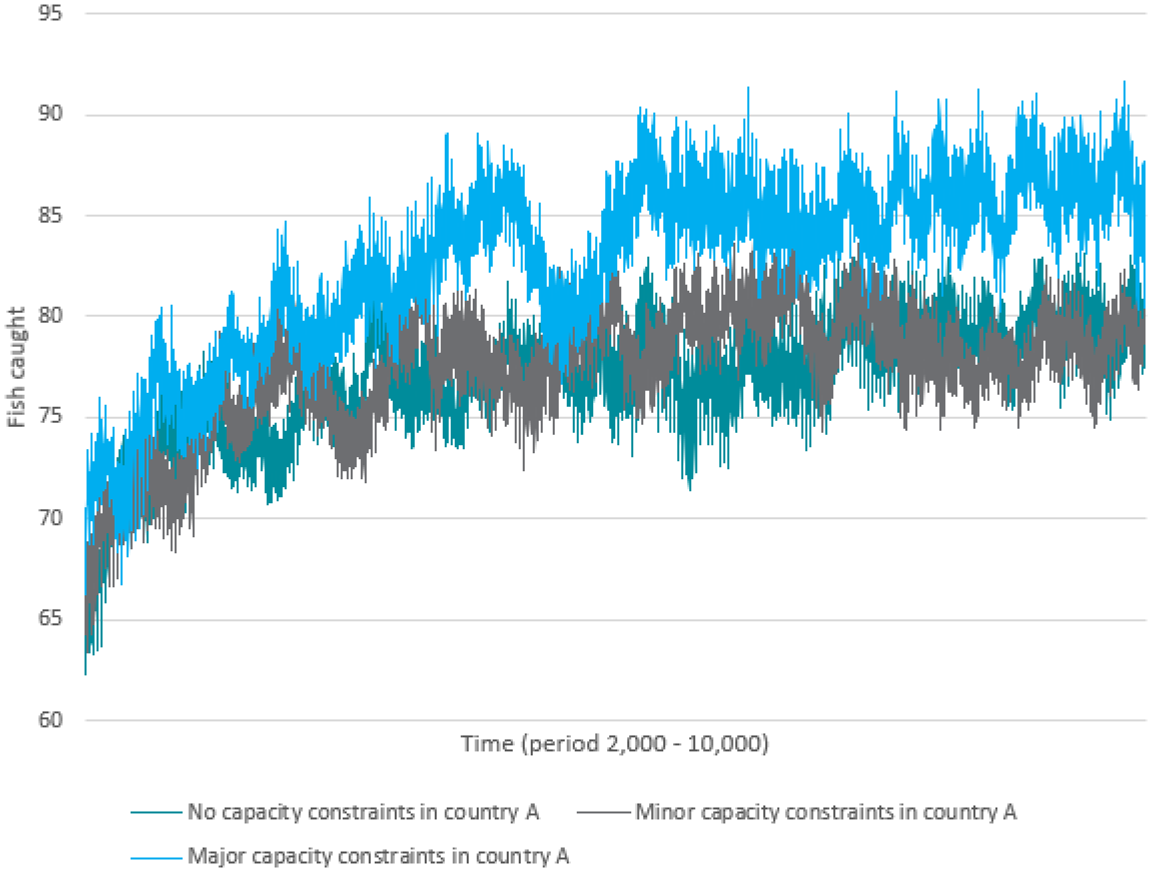
Table 20 Probability of sanctioning for four fishing strategies, scenario E, scenario M, scenario N

	Probability of being sanctioned after conducting IUU activities in country A's waters and landing catch at port in country A	Probability of being sanctioned after conducting IUU activities in country A's waters and landing catch at port in country B	Probability of being sanctioned after conducting IUU activities in country B's waters and landing catch at port in country A	Probability of being sanctioned after conducting IUU activities in country B's waters and landing catch at port in country B
Scenario E	49%	55%	55%	53%
Scenario M	45%	51%	46%	45%
Scenario N	36%	51%	41%	59%

Fishery yield

The preceding analysis has shown that the introduction of minor capacity constraints when there is full information sharing by both countries and a relatively high number of enforcement agents in each country has a limited effect on fishing vessels decision making and behaviours. This is because, the high risks of detection when conducting IUU activities at sea are sufficient to wipe out the vast majority of illegal operations. In the case of major capacity constraints, the average amount of fish caught each period hovers around 85 units in the long run – around 5 units higher than in the case of no capacity constraints (scenario E). This is due to the fact that IUU fishing activities are associated with a higher rate of biomass extraction, due to the lower cost curve.

Figure 61 Fish caught each period, scenario E, scenario M, scenario N



The share of fish that are caught legally – both in country A and country B – is significantly lower in scenario N (with major capacity constraints in country A) than in scenario E (with no capacity constraints). As a result, the average quantity of fish caught legally each period towards the end of the 10,000 period simulations is 74 units in scenario N – roughly 8% lower than in scenario E. However, this difference is more than offset by a substantially higher quantity of fish caught by illegal means in scenario N. Indeed, the average quantity of fish caught illegally each period is around 11 units higher in the long run in scenario N than in scenario E.

Figure 62 Fish caught legally each period, scenario E, scenario M, scenario N

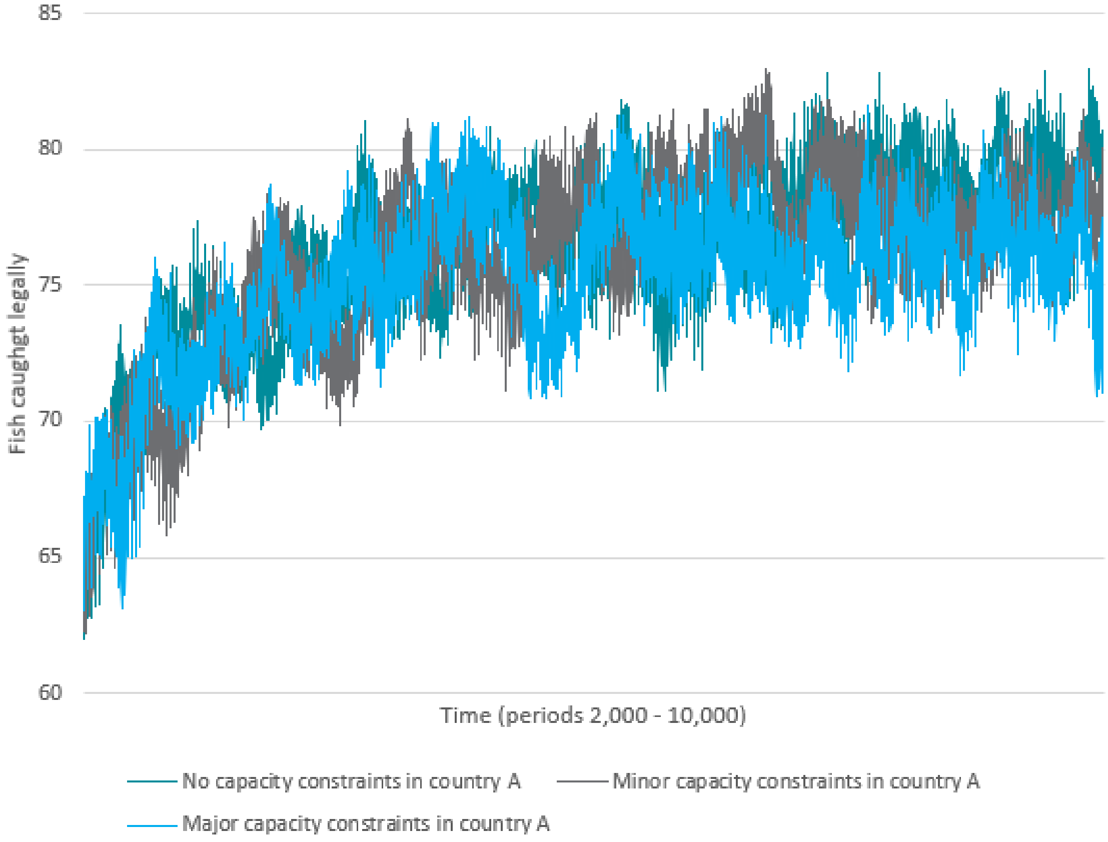
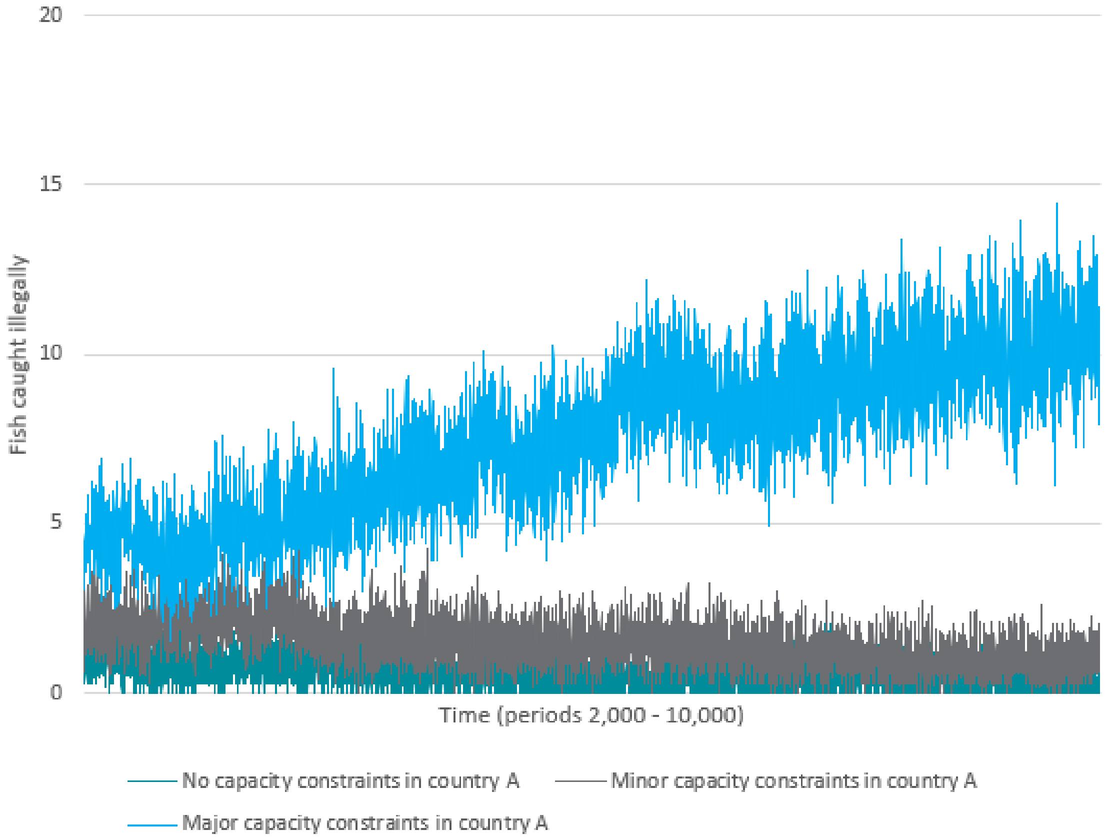


Figure 63 Fish caught illegally each period, scenario E, scenario M, scenario N



Over the 10,000 periods the average cumulative fishery yield rises from 790,925 in scenario E to 796,920 in scenario M, which reflects the marginal increase in IUU activities associated with the introduction of minor capacity constraints in country A. In scenario N, the cumulative fishery yield averages 839,624 units after 10,000 periods – 6% higher than in scenario E.

Table 21 Cumulative fishery yield after 10,000 periods, scenario E, scenario M, scenario N

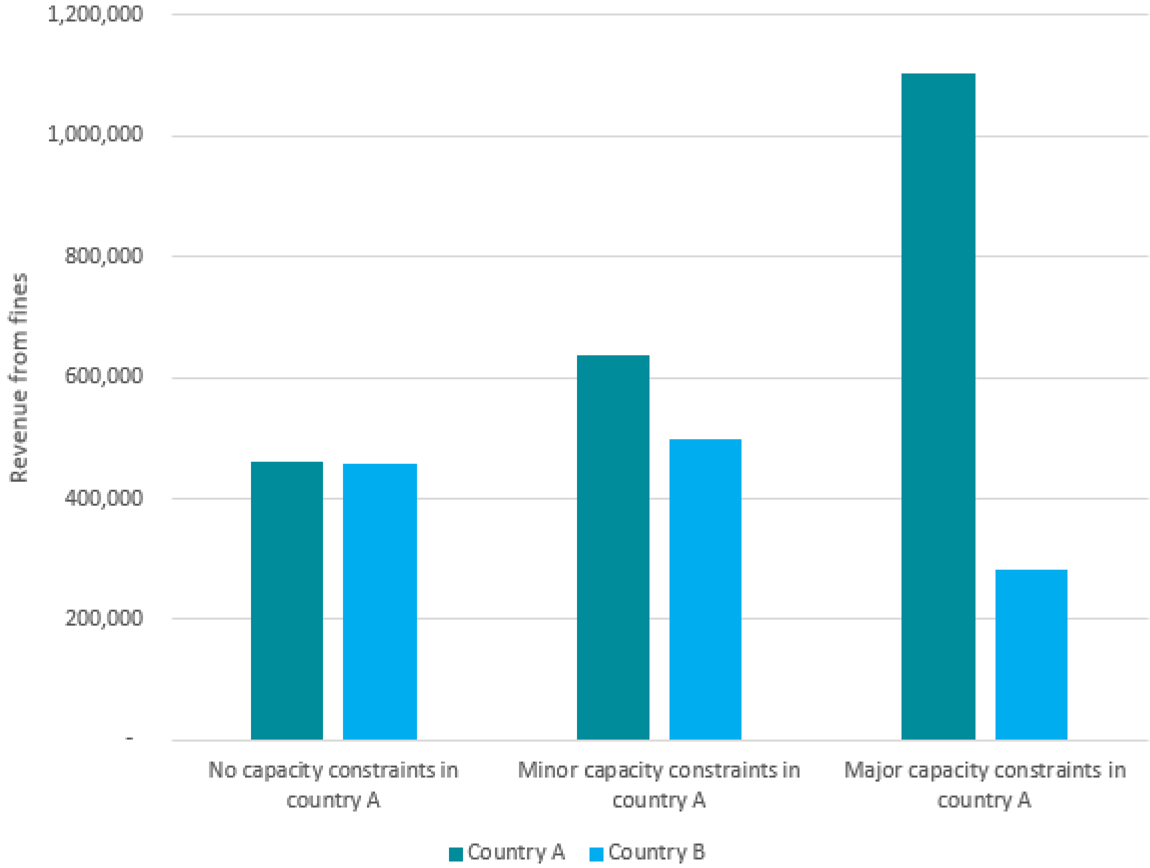
	Fishing yield after 10,000 periods	Legal fishing yield after 10,000 periods	IUU fishing yield after 10,000 periods
Scenario E	790,925	783,664	7,261
Scenario M	796,920	780,354	16,566
Scenario N	839,624	773,655	65,969

Revenue from fines for IUU activity

The revenue received by country A from fines for IUU activity increases significantly as capacity constraints are introduced, rising from 462,329 units in scenario E (with no capacity constraints) to 634,987 units in scenario M (with minor capacity constraints) and to 1,103,098 units in scenario N (with major capacity constraints). This is due to the increase levels of IUU activity that take place when capacity constraints are introduced, generating higher revenues from fines.

In the case of country B, there is an increase in revenue received from fines when minor capacity constraints are introduced at the port authorities in country A, which also reflects the slight rise in IUU activity taking place. However, when there are major capacity constraints in country A, the revenue from fines received by country B falls by 44% relative to the case of minor capacity constraints. This is because, the extent of the capacity constraints in scenario N mean that there is very little incentive for fishing vessels that have conducted IUU activities during a fishing trip to land their catch at the port in country B.

Table 22 Revenue from fines for IUU activities, scenario E, scenario M, scenario N



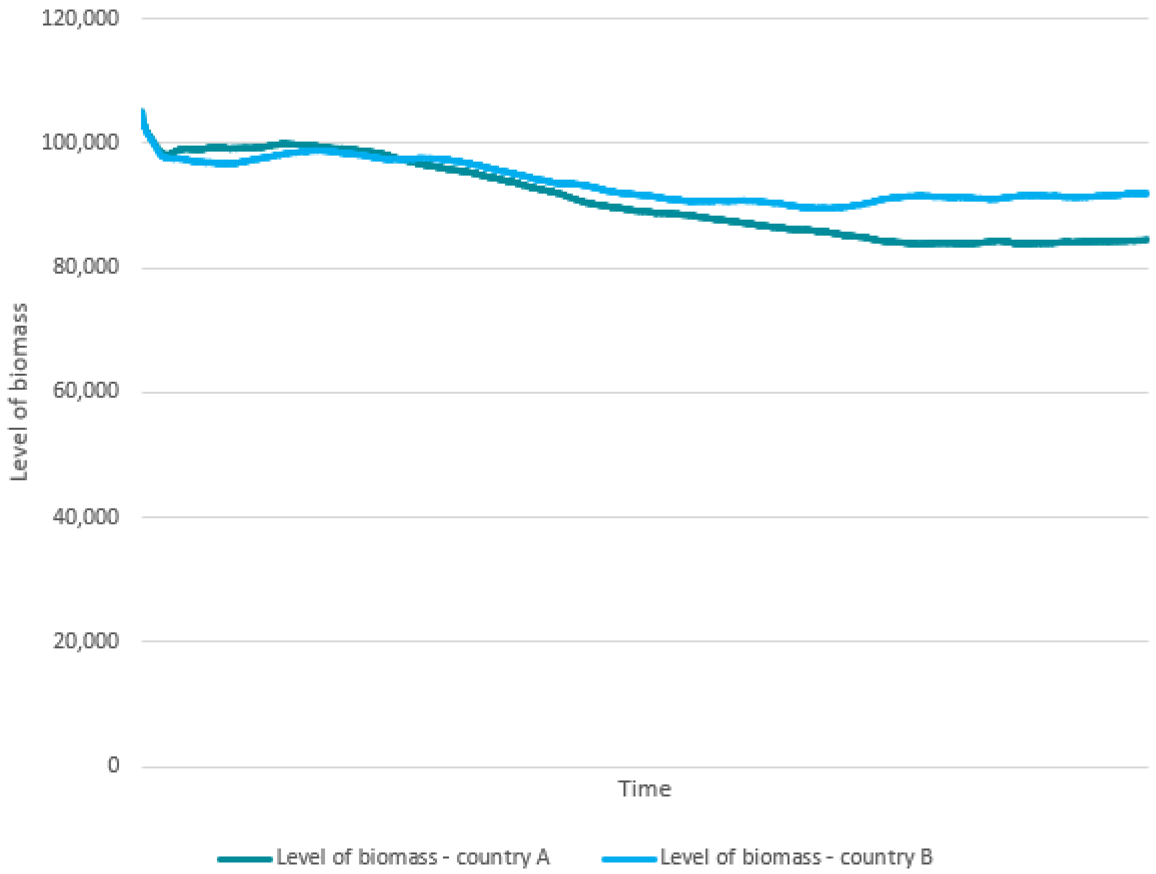
5.5 Bespoke scenarios O – P

The final two scenarios represent a more specific set of enforcement structures. Scenario O considers the case in which country A has a very loose enforcement framework. This involves just 5 enforcement agents, each with a radius of vision of 3 patches rather than the usual 5 patches. There is also a relatively low fine rate associated with IUU activities that amounts to half of the profits obtained during the fishing trip. Finally, the port in country A is subject to severe capacity constraints, meaning that for every four incoming fishing vessels that the port has been told have been acting illegally, just one will have the appropriate penalty imposed. Meanwhile, country B has 10 enforcement agents with a radius of vision of 5 patches. The fine rate for IUU activities is 100% of the profits obtained during the fishing trip, and the port is subject to minor capacity constraints. In terms of information sharing, country A's enforcement agents share 25% of their detection information with the port in country B while country B's enforcement agents share half of their detection information with the port in country A. Fishing vessels are also able to move freely across the sea border.

The modelling simulations for scenario O suggests that a low level of enforcement in country A contributes to a marked deterioration in the health of the shared fishery resource. Indeed, the level of biomass declines consistently in the early and middle stages of the simulations, only reaching an equilibrium level towards the end of the model runs. As would be expected, the level of biomass is lowest in country A, where the deterrent for IUU fishing activity is significantly weaker. After 10,000 periods, the average level of biomass in country A is just 84,465. This value is the lowest among all of the scenarios analysed thus far, highlighting how other enforcement parameters besides from information sharing – such as the fine rate and the effectiveness of enforcement agents – have a key role in determining the health of the fish population.

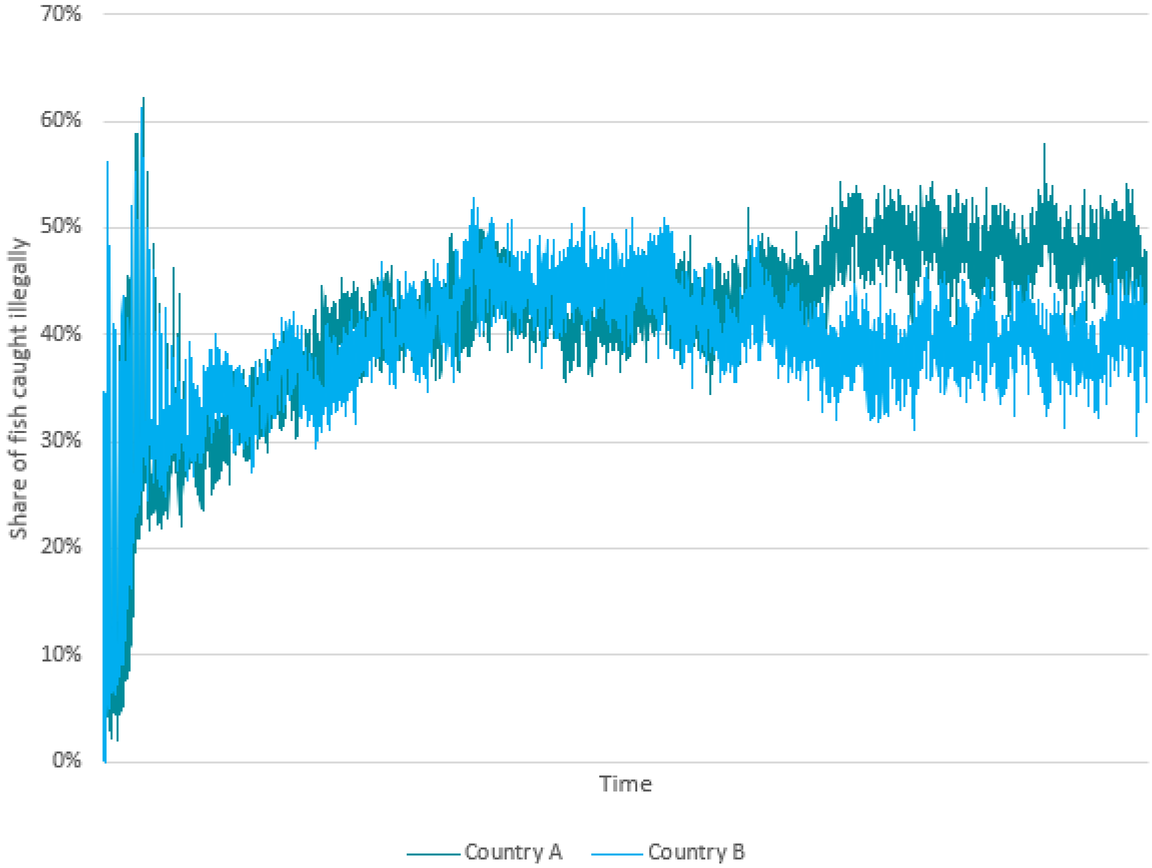
In country B, the level of biomass during much of the simulation period, reaching an average of 91,901 by the end of the 10,000 period simulations. This level is far lower than is observed in other scenarios in which country B has a relatively similar enforcement structure. The shared nature of the fishery resource means that unilateral changes by either country will inevitably generate externalities on the other. In this case, the very loose enforcement structure in country A has a significant effect on levels of biomass in country B, despite this country itself choosing to adopt a relatively robust framework.

Figure 64 Level of biomass, scenario O



The share of fish caught illegally rises sharply during the early stages of the modelling simulations in both countries. This is the primary driver of the steady decline in the level of biomass described previously. In the case of country A, the share of fish caught illegally eventually settles at around 45% - a higher share than in any of the other scenarios analysed, which again underscores the importance of other enforcement levers beyond information sharing. In country B, higher domestic enforcement standards mean that the proportion of fish caught illegally in the long-run is around 40% on average by the end of the modelling simulations. This is more than double the share that is observed in scenarios where country B shares the same amount of information with country A, but country A itself also has a stronger enforcement framework.[46]

Figure 65 Share of fish caught illegally, scenario O



Scenario P considers a situation in which both countries have a relatively high level of enforcement, with partial information sharing taking place in both directions. This means each country has 10 enforcement agents with a radius of vision of 5 patches, and that enforcement agents in both countries share half of their detection information with the port in the neighbouring country. So far, this description of scenario P aligns with scenario D (homogeneous enforcement structures with partial information sharing by both countries). There are, however, two key differences between scenarios P and D. Firstly, in scenario P, it is assumed that only half of fishing vessels are able to operate freely in both countries, while the remaining fishing vessels' operations are confined to their home country's waters. Also, in scenario P, country B imposes a fine rate that amounts to double the value of the guilty fishing vessel's profits (compared to 100% of the value of the fishing vessel's profits in scenario D).

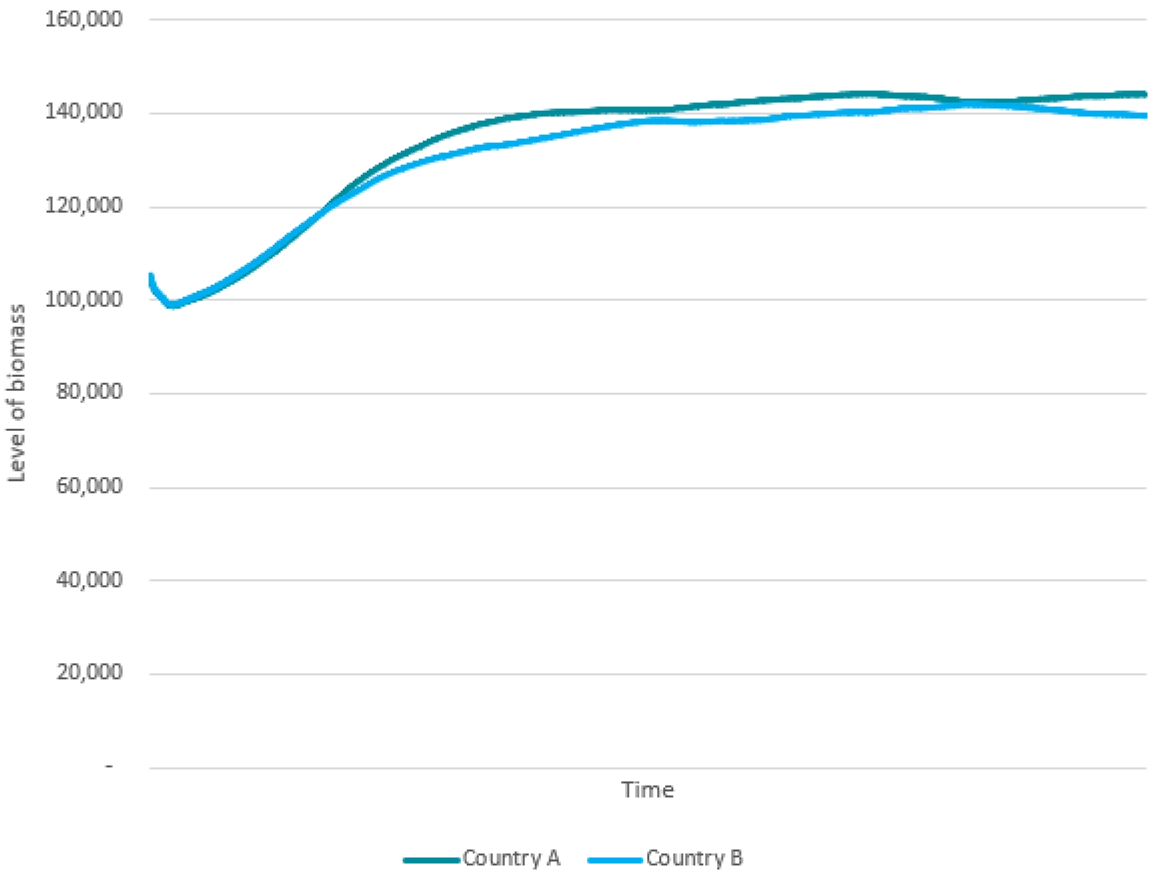
Figure 66 shows that there is no significant difference in the average level of biomass in country A and country B throughout the modelling simulations. On the surface, this is

46 Scenarios B and G are the closest equivalents to scenario M in terms of country B's enforcement structure, although scenario O is the only scenario in which the port in country B has capacity constraints. This will also have contributed to the difference in the average share of fish caught illegally in the long-run.

perhaps a surprising outcome given that country B has a higher level of enforcement via the more draconian fine rate. This result occurs because the higher fine rate in country B deters fishing vessels from conducting IUU activities in country A's waters before crossing the border to land their catch at the port in country B.

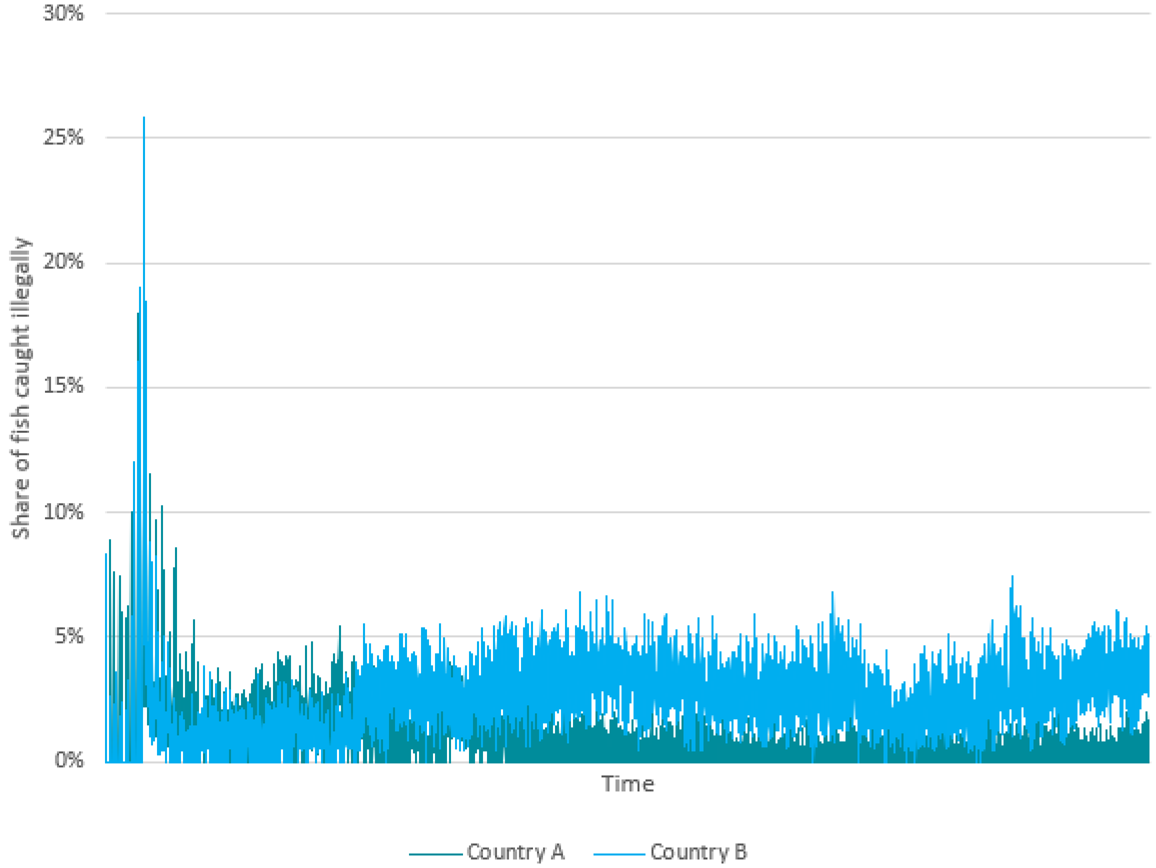
The long-run level of biomass across the two countries averages 283,437 in scenario P, compared to 266,068 in scenario D. This difference can be attributed to a combination of the higher fine rate in country B and the increase in the degree of border friction. Both of these features lower the frequency with which fishing vessels conduct IUU activities in one country before landing their catch in the neighbouring country, which is a key component of overall IUU activity in the case of partial information sharing.

Figure 66 Level of biomass, scenario P



As discussed above, country B's imposition of a higher fine rate on fishing vessels that have conducted IUU activities represents a significant positive externality for country A. This is because, when there is partial information sharing, the incentive remains for fishing vessels that are engaged in IUU activity to cross the border to land their catch in the neighbouring country. However, the high fine rate in country B in scenario P means that this approach is no longer viable for the vast majority of fishing vessels. Indeed, Figure 67 shows that the share of fish caught illegally in country A is consistently below 1% throughout most of the modelling simulations. In country B, the share of fish caught illegally is slightly higher, standing at an average of around 4% towards the end of the modelling simulations. The doubling of the fine rate in country B will push many fishing vessels with a tendency to conduct IUU activities towards country B's waters, where they are able to then cross the border to land their catch in country A with a lower risk of detection as well as a lower fine rate in the event that they are detected. This results in the higher share of fish being caught illegally in country B's waters. With that being said, the rate of IUU fishing is lower in both countries in scenario P than it is in scenario D. This is due in part to the introduction of border frictions, which eliminates for many fishing vessels the option of crossing borders in order to reduce the risk of sanctioning for IUU activities. This may have important policy implications when considering countries with different fisheries management policies.

Figure 67 Share of fish caught illegally, scenario P



6. Conclusions

The modelling and analysis that has been undertaken for this research provides a powerful illustration of the potential of information sharing as a tool to support the health of fish stocks and deter IUU fishing activities. This finding is consistent across a broad range of enforcement structures and information networks that have been analysed in this report. The refinements and extensions to the agent-based model that have been implemented during this research mean that these results can crucially be applied to an international setting with potentially divergent enforcement frameworks and varying degrees of border frictions. Moreover, the introduction of ports and the augmentation of fishing vessels' and enforcement agents' preferences and decision-making processes has allowed a more comprehensive selection of the nuances and practicalities that drive the behaviours of economic agents in the marine fishing industry to be represented.

In the case of both homogeneous and heterogeneous enforcement regimes, the total level of biomass across the shared fishery resource increases significantly with the rates of information sharing between the countries. This is the case both when there is one-way information sharing and when there is bilateral information sharing, although the long-run level of biomass is considerably higher when both countries opt to share information with their coastal neighbour. In the case of unilateral information sharing, the largest and most direct beneficiary is the country sharing the information, since IUU activities being conducted in that country's waters are now more likely to be sanctioned. However, the country receiving the information also sees an improvement in the health of its own fish stock under these circumstances. The population of fish in the model spans across both countries, meaning that they effectively manage a shared fishery resource. As a result, the fate of each country's fish stock is highly interconnected, and improvements in one territory will eventually filter through into the other territory. The fact that the primary benefits of information sharing in terms of the levels of biomass are felt by the country sharing the information means that systems of co-operation are sustainable, since these strategies align with countries' individual environmental sustainability goals. This type of information sharing is a core pillar of the Port State Measures Agreement. As of 30th September 2020, nine countries have registered voluntary commitments with the UN relating to the Port State Measures Agreement.[47] While these countries should be commended in laying out crucial steps that are being taken to tackle the issue of illegal fishing, the emphasis is typically placed on an enhancement of domestic enforcement processes and capacity. A notable exception to this is the South West Pacific region. Through the Pacific Maritime Security Program, a concerted effort is being made to improve co-ordination and co-operation among authorities in different countries in the region, for instance through the use of region-wide aerial surveillance and regional maritime co-ordination centres.

Information sharing increases levels of biomass through the deterrence of IUU fishing activities, which are associated with a higher rate of extraction. The introduction of information sharing drastically alters the menu of options that are available to fishing vessels at any given period. In the absence of information sharing, fishing vessels are able to operate illegally in one country before crossing the border to land their catch in the neighbouring port without any risk of detection. However, when detection agents begin to share information with the port in the neighbouring country regarding the fishing vessels that

47 Australia, the Maldives, Monaco, Myanmar, New Zealand, Norway, Kenya, Sweden, Tonga, Uruguay

they have detected conducting IUU activities, the risks of sanctioning rise markedly. The first order impact of this is that IUU fishing is a less attractive proposition for each vessel (irrespective of their inherent aversion to IUU activity), lowering the share of fish that are caught illegally. There is also a significant second order impact, brought about by the market entry and exit dynamics of the model: the introduction or expansion of information sharing has an adverse effect on the profitability of fishing vessels that tend to operate in an illicit fashion, since a larger share of their IUU activities will be detected and subsequently punished. This means that fishing vessels with a higher propensity to commit IUU acts are more likely to withdraw from the fishing market either due to a depletion of their wealth or successive periods of negative profitability. Over time, this leads to a structural shift in the characteristics of the fishing fleet whereby the average propensity to conduct IUU activities declines. This then leads to a corresponding fall in the prevalence of IUU actions. The overall result of these dynamics is that IUU fishing activity is largely wiped out in the long-run in the case of full information sharing and high levels of enforcement in both countries (scenario E). In scenario J – when there is full information sharing but country A has a looser enforcement framework – IUU activity lingers on in the low enforcement country, with around 9% of fish being caught by illegal means at the end of the 10,000-period simulation. However, this is still around a quarter of the share that are caught illegally in the equivalent scenario with no information sharing (scenario F).

Another outcome variable that has been analysed is the fishery yield that is realised under the various scenarios. A consequence of the decline in IUU activity in scenarios with more information sharing is that the average catch per period is slightly lower. However, it is important to note that the extent of the decline in yield is considerably smaller than the extent of the increase in the level of biomass. For instance, the long-run level of biomass is on average 55% higher in scenario E (with full information sharing by both countries) than in scenario A (with no information sharing), while there is only a 14% difference in the long-run yield each period. Also, while the total amount of fish caught is lower in situations with more information sharing between authorities in neighbouring coastal states, the amount of fish caught by legal means is nearly twice as high. This points to a considerable reallocation of the fishery yield from fishing vessels that commonly engage in IUU activity towards those that operate legally. This result also highlights that taking effective steps to deter IUU fishing can serve the dual purpose of rebuilding fish stocks while also boosting the yields associated with legal fishing operations.

For many countries, the revenue generated from fines associated with IUU fishing activity are an important source of funding for their regulatory structures. The results of the modelling show that in the absence of information sharing, the revenue received from fines is negligible, due to the fact that the vast majority of fishing vessels that conduct IUU activities choose to cross the border to land their catch, which eliminates the risk of sanctioning. Full information sharing can often lead to a drastic reduction in the prevalence of IUU fishing activity, which in turn limits the fine revenues that are received. With that being said, revenues are significantly higher in scenarios with full information sharing than they are in scenarios without any information sharing. Generally, fine revenues are maximised in scenarios with partial information sharing, since these conditions lead to a significant amount of lingering IUU activity in an environment in which at least some cross-border IUU operations are detected and sanctioned.

An important consideration is that many ports – due to an array of technological, logistical or institutional factors – may not have the capacity to act upon the information that they receive from enforcement agents (either from their own country or from another coastal state). The results of the modelling show that capacity constraints do significantly erode the benefits of information sharing in raising levels of biomass and discouraging IUU fishing activity. With that being said, the total long-run level of biomass in a scenario with major capacity constraints at the port in the low enforcement jurisdiction but full information sharing between both countries (scenario L) is still around a quarter higher than in the case of no capacity constraints and no information sharing (scenario F).

6.1 Topics for future research

The research presented in this report – as well as the previous iteration of the agent-based modelling carried out by Cebr and The Pew Charitable Trusts – focussed on the relationship between the occurrence of IUU fishing and countries' enforcement regimes i.e. levels of information sharing, fine rates, the number of enforcement agents etc. In other words, it has examined how varying the ways in which regulations are enforced can influence outcomes of interest, such as levels of biomass, fishery yield or the share of fish caught by legal means.

Regulatory divergence

The modelling framework developed during the course of this research provides an excellent baseline from which to explore how changing the regulations themselves can affect the economic and biological systems of fishing markets. The types of parameters that could be analysed include the methods of fishing that are prohibited (which can be modelled by augmenting fishing vessels' cost curves), the number of fishing vessels that are granted a license to fish in each country, and the degree to which fishing vessels are allowed to move between countries. This exercise would provide useful insights into the types of regulations that are most effective in delivering the desired outcomes for fisheries, both from an economic and ecological standpoint. By implementing these features in a multi-country model, it would be possible to examine how regulatory divergence or alignment can impact affected countries, looking in particular at the externalities produced by changes to one country's regulations on other countries with a stake in a shared fishery resource.

Fishing quotas

In the modelling conducted to date, IUU activities have been based on fishing vessels avoiding license costs or using prohibited equipment or processes in order to catch their fish more cheaply. However, a significant share of IUU activity is also accounted for by the breaching of fishing quotas. Augmenting the ABM to include fishing quotas would add a further avenue via which fishing vessels can operate illicitly. This change would also add to the model a further policy lever for regulators: in addition to adjusting fine rates, port capacity, information sharing and the number of enforcers, regulators could also alter their quotas in order to manage their fisheries.

Strategic enforcement agents

In the modelling runs conducted thus far, the regulatory and enforcement strategies adopted by each jurisdiction are set exogenously, with parameters varying depending on the specific scenario. This represents a significant simplifying assumption, since regulatory authorities are in fact strategic agents. In the current model, fishing agents are treated as strategic agents that maximise their utility, which is related to their expected profits as well as their level of aversion to operating illegally. In an expanded version of the agent-based model, regulatory authorities could also be treated as strategic agents, with a number of factors feeding into their utility function, ranging the prevalence of IUU activities to revenue from fines and policy imperatives that might reflect environmental concerns such as ecosystem sustainability. These autonomous agents would then design their enforcement strategies in a way that maximises this utility, for instance by adjusting the number of enforcement agents they deploy, the amount of information they share with neighbouring countries and the size of the fines they impose on vessels that are found to have operated illegally. This utility maximisation would be subject to a range of financial and / or operational constraints. This augmentation of the agent-based model would provide insights into how regulatory authorities may adjust their strategies in response to the actions of nearby countries, the availability of enforcement technologies, the provision of financial or enforcement resources and changes to the international regulatory environment. Of particular interest would be the degree to which countries' enforcement strategies are limited by budgetary constraints. This in turn would allow us to examine how the alleviation of these financial constraints would affect regulatory approaches and the subsequent impacts on levels of biomass and the prevalence of IUU activities.

Additional scenarios

Work could be done to develop scenarios that more specifically explore the issue of **path dependency -** which is a much more realistic scenario when considering real world applications. For many of the scenarios above, one could explore the efficacy of introducing information sharing and enforcement changes at different points in time, and whether this affects the end outcomes, compared to the current context where the policy changes are applied at the beginning of the simulations. There are important questions to be answered regarding the speed versus scope of action and whether delaying policy action (to iron out international agreements for instance) can result in permanently lower biomass levels. It may be also important to consider time lag between a change to enforcement and / or regulatory parameters and changes in various outcomes of interest such as levels of biomass or the prevalence of IUU activity - especially in light of government policymaking and how this might have a limited window in which results need to come through. The extent of this time lag will often impact policies, since policymakers may require tangible short-term progress to justify their decisions.

The simulations presented in this report hold constant a number of key economic, regulatory and environmental variables, in order to isolate the effects of information sharing. The next stage would be to "stress test" these findings in order to establish the degree to which these results apply in a variety of different contexts. For instance, the simulations could be repeated for environments with higher rates of biomass movement, which would be more reflective of highly migratory species such as tuna. In these scenarios, it would be expected that there is an even greater interdependency between neighbouring coastal states, which in turn would increase the impacts of information sharing and the externalities generated by unilateral changes in enforcement or regulatory approaches. The majority of the scenarios analysed in this report assume an absence of border frictions, such that fishing vessels are able to fish and land their catch in whichever country is optimal for them. In future work, we could examine how the research findings regarding the effectiveness information sharing are altered when the assumption of a relatively open sea border is dropped.

Further model expansions

There are several areas where the existing model can be expanded or refined. One avenue to explore would be moving from a fine rate that is proportional to the profits from the entire fishing trip to one that is fixed in size. This amendment would better capture the enforcement structures that are in place in certain jurisdictions. Another adjustment would be to augment fishing vessels' cost functions, such that their costs are related to the density of biomass in their area of operation. This would reflect the reality that fishing costs are higher in locations where the biomass has been significantly depleted. This change would likely lead to a lower share of fishing activity being carried out close to ports.

Expanding the model environment to a full three-country system would represent a further step forward in capturing the interactions that take place between independent enforcement structures within larger international fisheries. An area that would be particularly interesting to study would be the degree to which the various externalities described in this report associated with unilateral changes to regulatory procedures apply to non-adjacent but relatively proximate coastal countries. Larval dispersal is an important channel through which activities in one jurisdiction produce spill-over effects for nearby areas. This could be modelled by introducing an additional term to the biomass growth function, which captures the spawning of new biomass at a rate proportional to the level of biomass in other parts of the model at an earlier point in time. This dynamic would lead to a closer relationship between fishing intensity in one part of the model environment and levels of biomass in other parts of the model environment.

Appendix A: Levels of biomass during individual model simulations

Figure 68 Level of biomass during individual model simulations, scenarios A - E

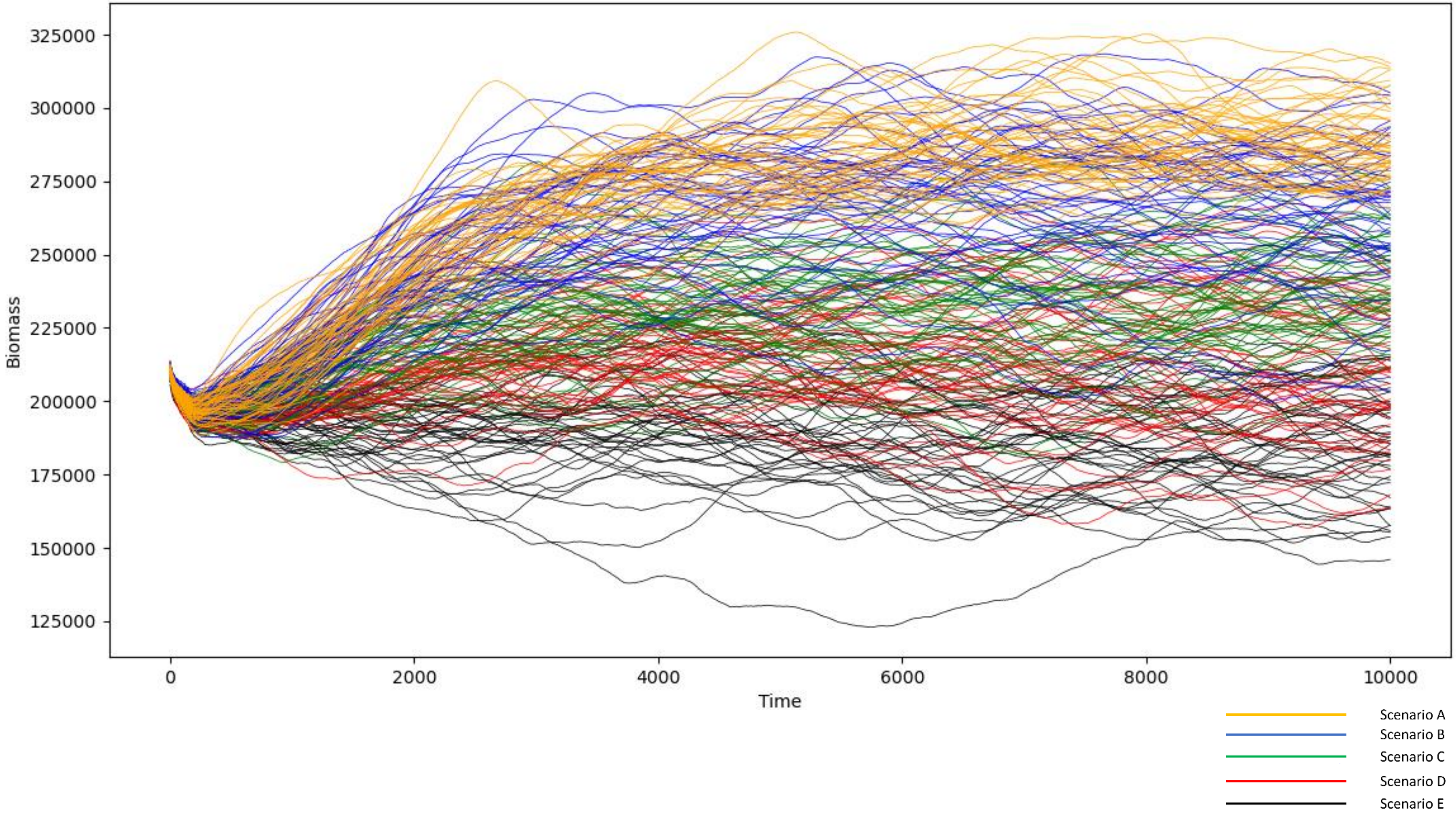


Figure 69 Level of biomass during individual model simulations, scenarios F - J

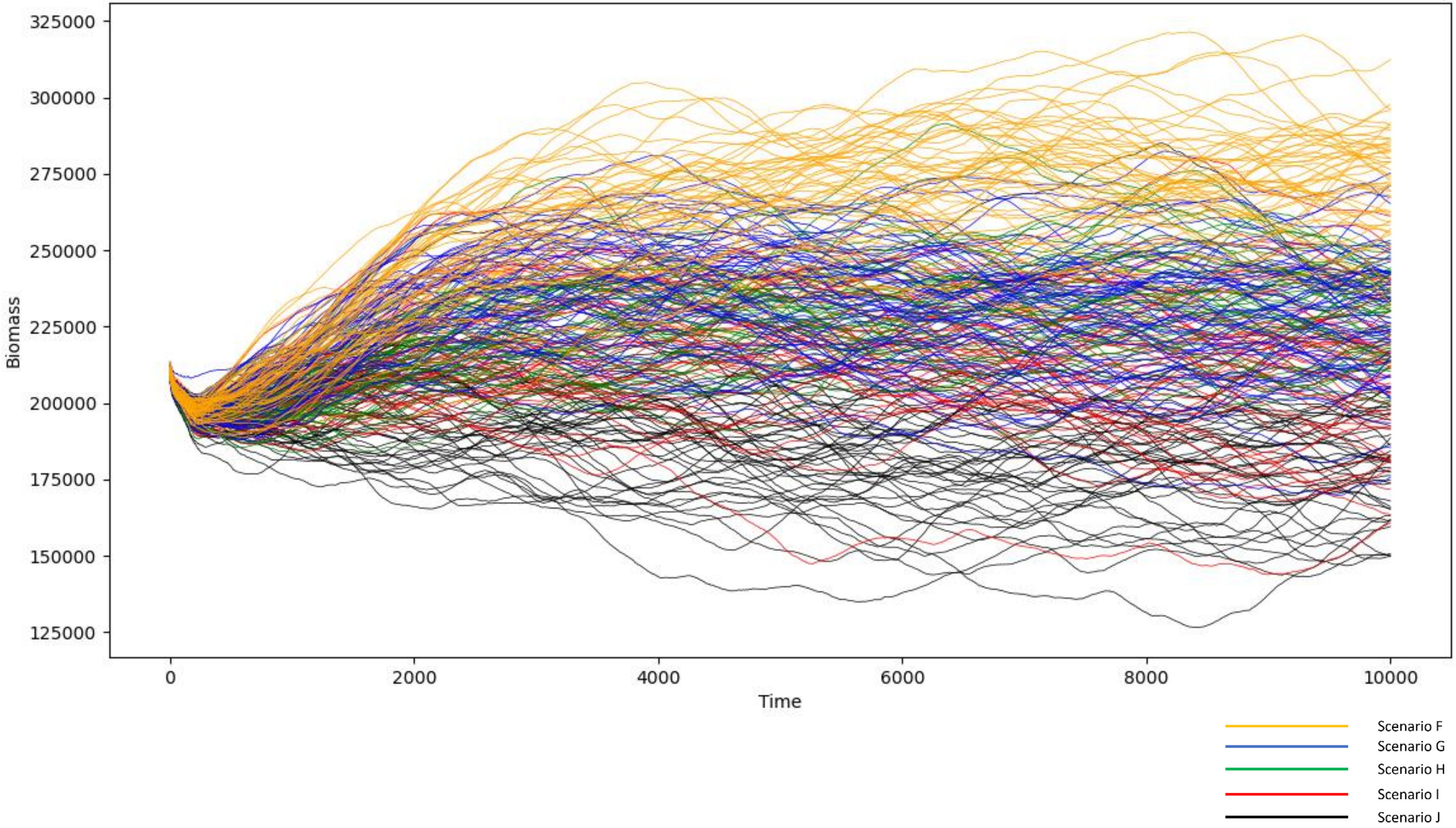


Figure 70 Level of biomass during individual model simulations, scenarios J - L

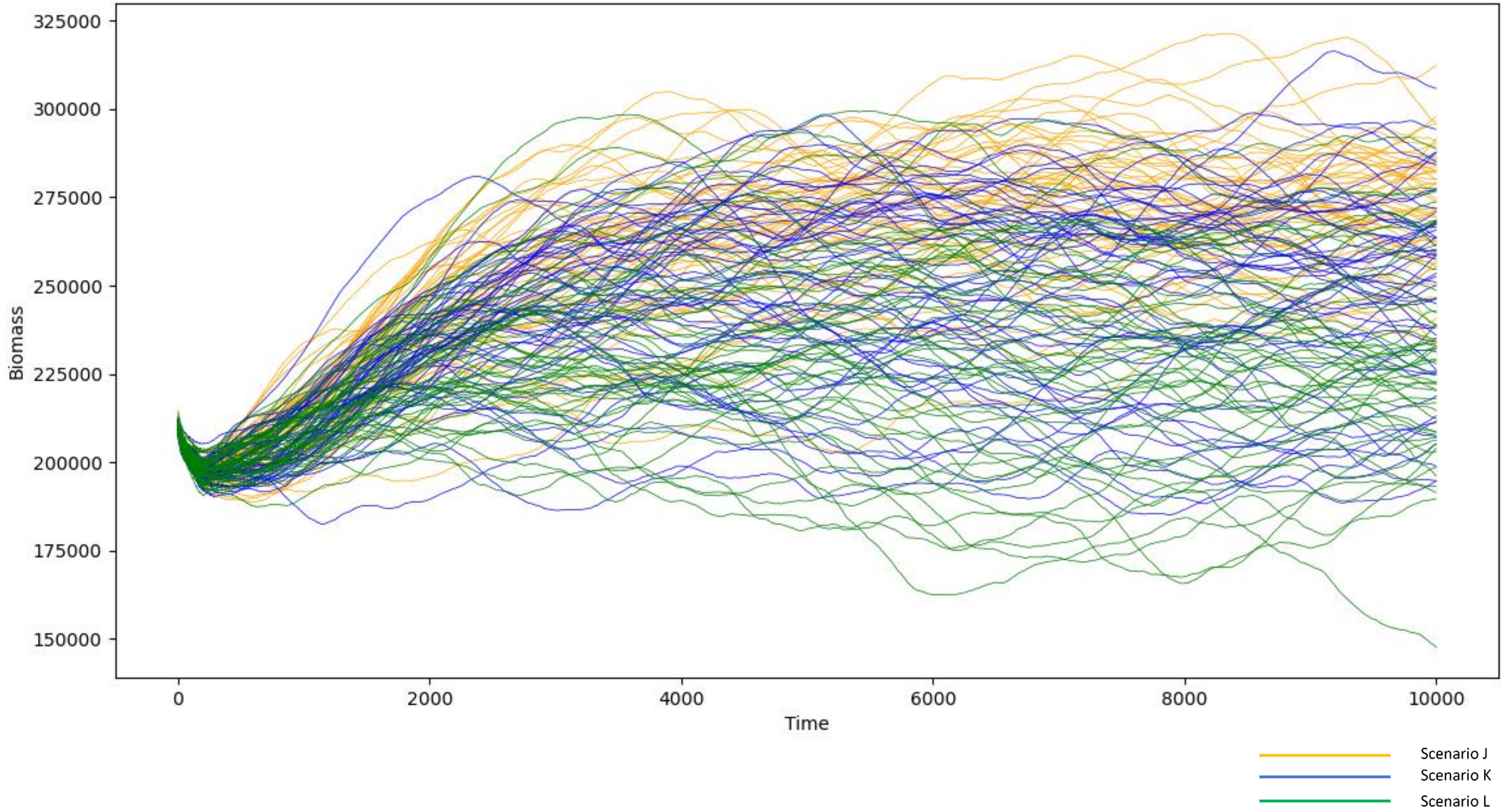


Figure 71 Level of biomass during individual model simulations, scenario E, scenario M, scenario N

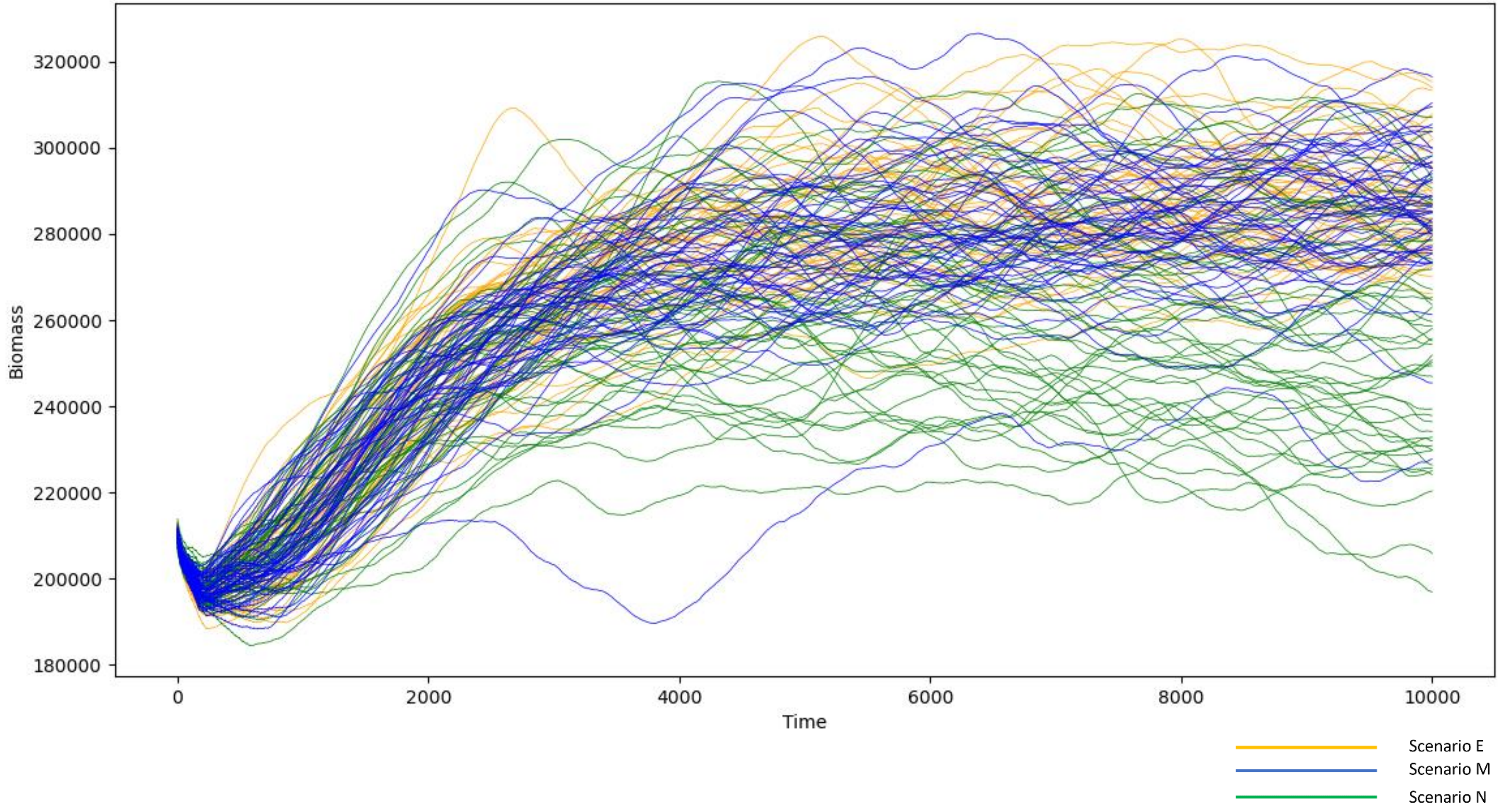


Figure 72 Level of biomass in country A and country B during individual model simulations, scenario O

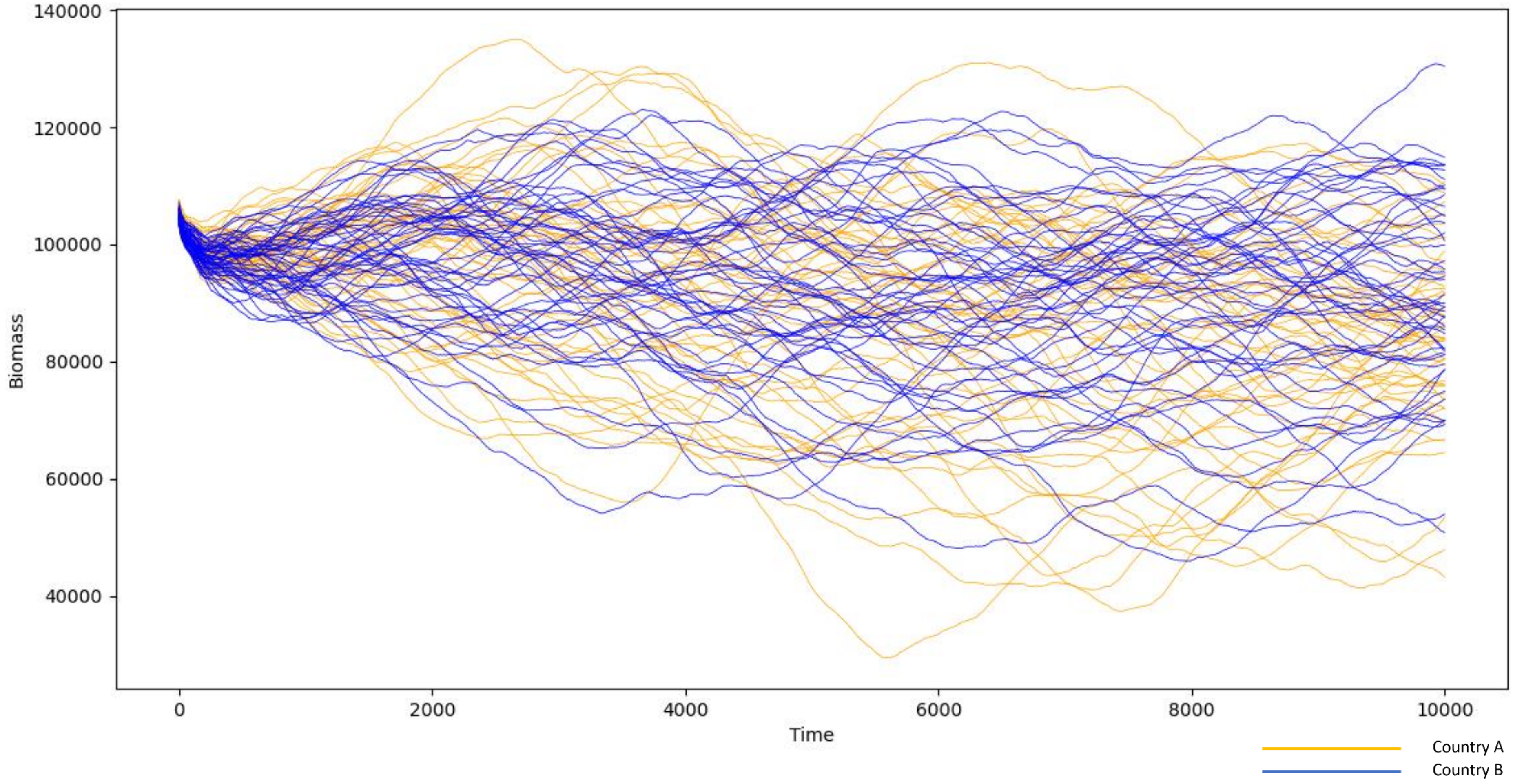
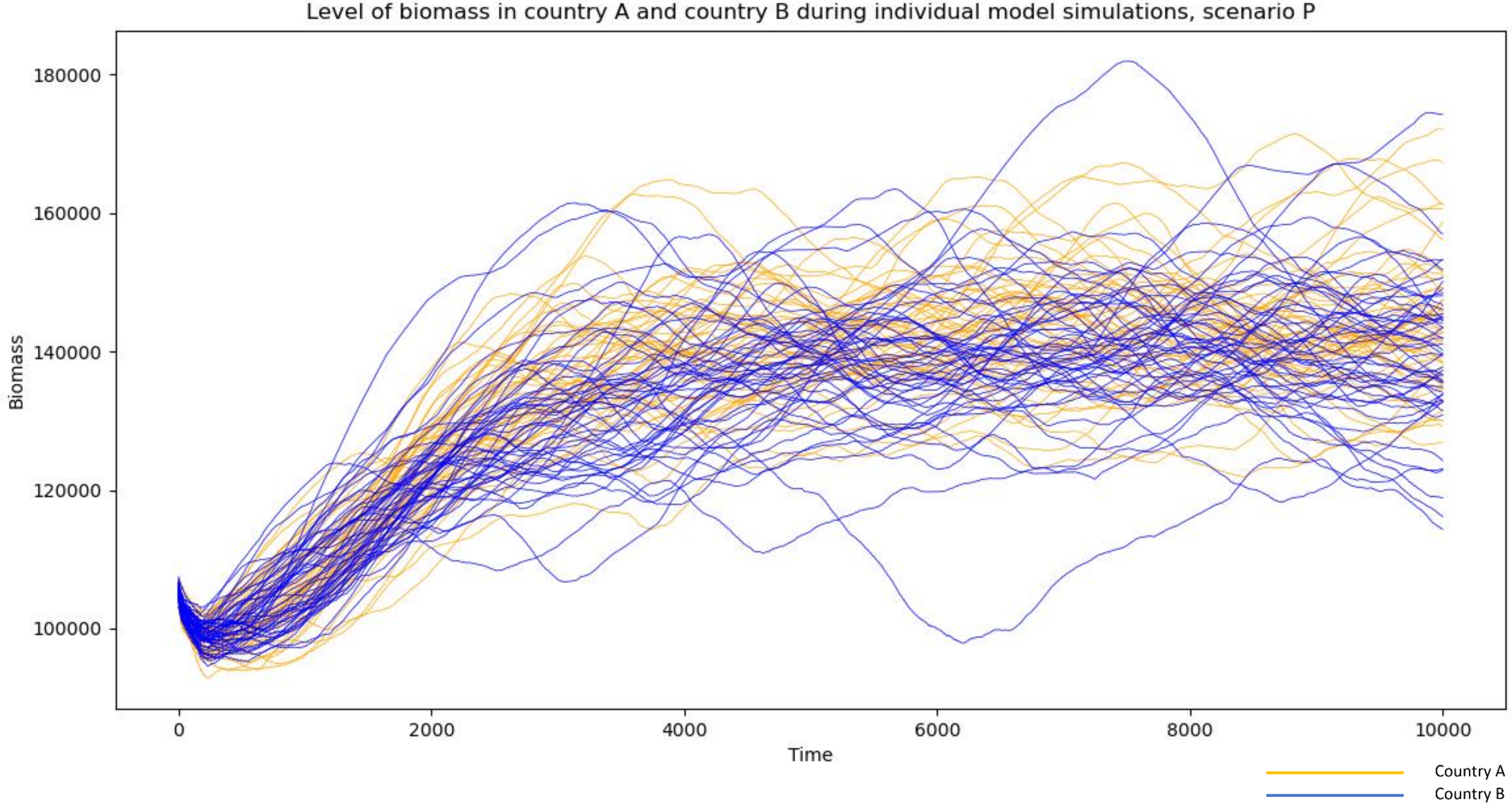


Figure 73 Level of biomass in country A and country B during individual model simulations, scenario P



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