To pollute or not to pollute? Exploring MARPOL Efficiency in the Adriatic Sea

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This study explores the efficiency level of the current international regulatory framework (MARPOL) in preventing sea pollution during maritime transportation. We employ a game-theoretic approach that models the decisions of shipowners and countries, with respect to the treatment and disposal of waste, where shipowners' decisions are based on comprehensive estimations of all waste management costs for all categories of waste (i.e. all MARPOL Annexes) differentiated across six types of standard risk vessels, while countries' decisions are based on estimates of all societal costs of (im)proper ship waste management. We focus on the Adriatic Sea case study and evaluate the game separately for members and non-members of the Paris Memorandum of Understanding (Paris MoU). Our main results seem to indicate that shipowners are generally motivated to be environmentally friendly if sailing Paris MoU waters. Otherwise, shipowners are merely motivated to pollute, due to low inspection rates and expected fines.

KEY WORDS

~ Maritime transportation
~ Sea pollution
~ MARPOL
~ Paris MoU
~ Game theory

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1. INTRODUCTION

The official UNCTAD (2020) statistics report more than 167,000 vessel arrivals in 2018, carrying passengers and cargo to ports in the Adriatic Sea, with a purpose of transport, commerce, tourism and recreation. A number of international conventions, as well as EU Directives and national laws, regulate these activities with a special emphasis on the environmental impact of maritime transport and the prevention of pollution. Despite the latter, the Adriatic Sea remains a heavily polluted sub-region of the Mediterranean. On the one hand, in 2019 on the Adriatic coast the median number of waste items per 100 meters of coastline was 547, compared to 377 (the average of medians) of other Mediterranean coasts (ISPRA 2022). On the other hand, tank washings and illegal discharges in the Adriatic Sea are not rare, with most of the oil spills being released during night-time and beyond territorial waters (Morović et al. 2015).

Public attention often couples marine pollution with oil pollution, although the latter makes just one out of various negative environmental effects rooted in marine transportation. The International Maritime Organization (IMO) set forth a series of international regulations addressing all the environmental impacts of maritime transport, from oil pollution to ballast water discharges, garbage and sewage discharges and air pollution (so-called MARPOL regulations). Complying with all these environmental regulations for a shipowner also means incurring additional operating costs. Already in 2003, OECD notes how port inspections reveal that nearly half of the vessels inspected violate at least one aspect of the rules concerning stowage and disposal. Furthermore, savings derived by not complying with IMO's rules lead to a reduction of costs, which can be used to derive an unfair advantage in the highly competitive ship market (OECD 2003). Lately, special attention has been devoted to compliance with the environmental regulation in the cruise industry, given the enormous average amount of waste cruise ships are causing. The US Bureau of Transportation Statistics (2020) estimate that a large cruise ship (3000 passengers + crew) in a one-week journey generates almost 800,000 litres of sewage, 3.79 million litres of grey waters, 500 litres of hazardous waste, 8 tons of solid waste, and 95,000 litres of oily bilge waters. If not treated and disposed properly (in ports), these can lead to adverse health, welfare, and environmental effects. Although the amount of waste created by other type of cargo and passenger vessels is much lower, if not properly treated and disposed, it can also result in environmental damages beyond repair, especially in the Adriatic Sea that is semi-enclosed and that exchanges water with the Mediterranean Sea with a rate of 1-5 years (Morović et al. 2015). A large oil spill accident , as well as an improper treatment and disposal of all sorts of waste, could put down all Adriatic economies, particularly those that largely rely on tourism and fisheries.

The goal of this study is to discuss pollution decisions of shipowners and countries stemming from maritime transportation, while addressing all MARPOL Annexes, i.e. all possible pollution sources, from oil to sewage discharges. In particular, we investigate the eventual decisions of shipowners with respect to the treatment and disposal of waste, given the monitoring and controlling roles of the country, and try to answer the following main question: Is MARPOL regulation efficient in preventing maritime pollution?

In order to assess the efficiency of the regulation in a suitable way, we have decided to base the analysis on the Adriatic Sea case. There are six states that have shorelines along the Adriatic Sea, i.e. Albania, Bosnia and Herzegovina, Montenegro, Croatia, Italy, and Slovenia, with only the last three being members of the Paris Memorandum of Understanding (Paris MoU). The latter fact is crucial for our analysis, because it enables us to study the pollution problem and contrast the decisions of shipowners and countries, differentiating across Paris MoU members and non-members. Namely, we assume that Paris MoU members are more environmentally friendly oriented and thus inspect vessels more often than non-members, meaning that in such a setup the international regulation on safeguarding marine pollution should be efficient at most.[1] Given the strategic nature of the relationship between countries and shipowners, we have employed a game-theoretic approach (Nash equilibrium analysis, in particular) to analyse their decisions. Since vessels come in all shapes and sizes, serve different purposes and produce different amount of waste, doing the analysis on only one representative vessel type would lead to biased results. Being aware of that, we have decided to analyse several main types of vessels, as has previously been done, for example, by van Hammen & van Hammen (2017), among others. We differentiate across six types of standard risk vessels: three types of tankers, cruise ship, fishing vessel, and Ro-Ro passenger ship. This choice is mainly based on two reasons: on the one hand, it allows comparability with other studies (e.g. Bachér and Albrecht 2013), while on the other hand, and more importantly, it permits to exploit, in the best possible way, the available data sets and sources needed for the estimation of pollution costs. With six countries and six vessel types, this study encompasses a set of 36 strategic situations, based on estimated monetary payoffs, assumed to be the utilities of shipowners and countries. These utilities describe the preferences of interacting parties and include an extensive set of costs of legal waste treatment and disposal (per type of waste and per category of vessel), as well as of external costs in case of an illegal discharge of waste in the Adriatic Sea. In order to take into account all of that, our comprehensive estimation is based on multidisciplinary data spanning from 2008 to 2018. On the one hand, costs of proper waste treatment and disposal are estimated based on average waste amounts per waste category and per ship, along with their respective treatment of costs per countries. On the other hand, assuming that illegal discharges damage health, tourism, fisheries, as well as the environment and ecosystem, we estimate and monetarise all of these damages per type of vessel, as well as per country, using different economic and non-economic data.

Our results show that, in case of Paris MoU members, shipowners are generally motivated to be environmentally friendly, while in case of non-members, shipowners of smaller vessels are merely motivated to pollute, because inspection rates and, consequently, expected fines, are too low to deter them from illegally discharging waste in the Adriatic Sea. In particular, when a shipowner in charge of a medium tanker, large tanker, or a cruise ship, is sailing in Croatian, Italian, or Slovenian waters, fines and probabilities of being inspected, i.e. inspection rates, are high enough to prevent them from polluting, regardless of the country's decision about the monitoring and inspection level. Moreover, although the solution of the game does not involve a dominant strategy, shipowners of smaller vessels, i.e. small tankers, fishing vessels, and Ro-Ro passenger ships, are also likely to act environmentally friendly when sailing the same waters. The same conclusions regarding smaller vessels do not hold in case of Paris MoU non-members, though. In particular, our game-theoretic analysis for Albania, Bosnia and Herzegovina, and Montenegro suggests that, due to the low probability of being inspected, a shipowner of a smaller vessel is always better off by polluting, regardless of the monitoring level of the country, i.e. being environmentally unfriendly saves them additional costs and increases profits. This indicates that eventual correction of fines and/or inspection rates can be an effective instrument to

1. *Worth mentioning is that the European Environment Agency (EEA) shows that Albania, Bosnia and Herzegovina, as well as Montenegro, exhibit among the lowest levels in progressing towards targeting waste and marine litter (European Environment Agency 2020).*

motivate shipowners of all vessels to act in an environmentally friendly way. Therefore, MARPOL is mostly effective and efficient if coupled with a good monitoring system, such as port state controls, which, besides preserving the environment, fosters sustainable economic growth. In addition to these findings, we also find that in situations where interacting parties do not have strictly dominant strategies, countries are more likely to select less costly but also less environmentally friendly options, which is not the best long-term strategy to preserve the environment.

This paper contributes to the literature in several ways. First, by proposing two games that address the pollution problem differently for members and non-members of Paris MoU, this study enables an assessment of the efficiency of the MARPOL regulation in preventing marine pollution. Second, since the interacting parties are allowed to randomise between their two actions and utilities are cardinal, meaning that utilities not only tell which pair of chosen strategies is better compared to other pairs of chosen strategies, but also by how much, mixed Nash equilibrium always exists (Nash 1950, 1951) and has a meaningful interpretation. This means we are able to predict a steady state for each of our games. The cardinal utilities are assessed using real data per vessel type and for all six countries, covering economic, marine, transport, health, and ecosystem issues. To the best of our knowledge, this paper is a rare example of evaluating all of the utilities using real data. Third, this paper is the first to embrace and estimate costs stemming from all potential pollution sources, i.e. oil spills, liquid waste, solid waste, hazardous waste, and air pollution, and therefore sets forth a clear picture about the effectiveness and efficiency of the current international regulation. This is especially relevant in the long-run perspective and achievement of sustainable growth levels, given that, among others, pollution causes severe damages to resources for future generations as well. Fourth, the comprehensive assessment per six types of vessels, as well as per six Adriatic countries, proves to be relevant from the policy implication perspectives, given that eventual correction of fines and/or inspection rates, i.e. more rigid implementation of MARPOL, results to be an effective instrument to motivate shipowners of all vessels to act in an environmentally friendly way.

The paper is structured as follows: after this introductory section, Section 2 gives a brief overview of the literature using game theory modelling to address environmental issues and problems, and Section 3 details the regulatory framework of preventing marine pollution. The following Section 4 gives a comprehensive explanation of the model and presents the estimation of all the needed variables. Section 5 discusses the results of the Nash equilibrium analysis. The last section is reserved for concluding remarks.

2. LITERATURE REVIEW

The last decades have witnessed a growing literature in the field of environmental policies and problems employing game theory. This is particularly evident in the field of transboundary pollution problems (Fernandez 2002; Bayramoglu 2006; Hay 2010, among others), water resources management (Wei and Gnauck 2007; Madani 2010; Dinar and Hogarth 2015, among others), and other strategic situations related to climate change and pollution control (Li and Tapiero 2010; Ahlvik and Pavlova 2013; Yu et al. 2017; Yang et al. 2018, among others).

From the perspective of our research, the works by Li and Tapiero (2010) and Yang et al. (2018) have turned out to be the most influential. On the one hand, Li and Tapiero (2010) demonstrate that maritime control and inspection policies can be modelled as a random payoff game between a shipowner and a port authority. Yet, this study also shows that the analysis of random-payoff games is rather cumbersome and very difficult to perform without specific numerical computer calculations. On the other hand, Yang et al. (2018) use a game between port authorities and shipowners to examine inspection policies. In their model port authorities decide whether to inspect the arriving vessels or not, whereas shipowners decide whether to put high or low efforts in maintaining their vessel.[2] In contrast to Li and Tapiero (2010), Yang et al. (2018) use standard Nash equilibrium analysis combined with Bayesian network model in determining the optimal inspection rates for port authorities and the optimal maintenance rates for shipowners. Their comprehensive analysis is based on bulk carriers' data from 2015 to 2017.

Focusing on the oil pollution solely, van Hemmen and van Hemmen (2017) underline how the latter still presents an unsolved international problem. This is due to the conflict of interest between the shipowners, whose main goal is profit, and the society, whose primary goal is maintaining a clean environment. The authors model the oil pollution problem as an individual decision problem, in which a shipowner must decide whether to comply with international regulation (i.e. MARPOL Annex I on the prevention of oil pollution, in particular).[3] To make a decision, a shipowner compares the costs of compliance to the risks of being inspected and decides on the basis of a cost-benefit analysis. Van Hemmen and van Hemmen (2017) conclude that shipowners of tankers, containerships, and bulk carriers are better off complying with international regulation, while this is not true for shipowners of passenger vessels. This is different from OECD (2003) that seems to indicate that polluting the environment makes (all) shipowners better off.

2. *High efforts guarantee a standard safety of the vessel, while low efforts maintain the vessel at a sub-standard safety level.*
3. *Details on the maritime regulation framework are presented in Section 3.*

Therefore the current literature shows that shipowners are better off by complying with international rules regarding the oil pollution, which is usually considered the utmost maritime pollution problem. But what about other sources of pollution, such as sewage, garbage, or harmful substances? Is MARPOL efficient in preventing pollution stemming from these sources as well? During the last decades we have witnessed that garbage, and sewage in particular, exceed the oil pollution problem and present a significant threat for the environment and ecosystem (European Environment Agency 2007, among others). This is exactly what this paper focuses on. It seeks to contribute towards a bridging shipowners' problem to countries' problem in complying with MARPOL regulation by contrasting shipowners' decisions made when sailing in waters of Paris MoU members with those made when sailing in waters of Paris MoU non-members. Although the relevant literature addresses such issues from a theoretical, rather than empirical perspective, we rely on real data to provide support for theoretical outcomes. In particular, we extend the pollution problem to all MARPOL Annexes (recall, van Hemmen and van Hemmen (2017), studying only oil pollution), while covering six types of vessels (recall that Yang et al. (2018), including only bulk carriers). Assuming that profit is the main goal of shipowners and sustainable growth the main objective of countries, we concentrate our analysis on the costs stemming from proper and improper waste treatment and try to contribute towards the literature, with an extensive set of empirical estimates of private, external, and social costs, based on real data. This also includes monetarising ecosystem damages and output losses, which are difficult to assess in practice.

3. REGULATORY BACKGROUND

The main organization that serves to guide the international maritime transport is the International Maritime Organization (IMO). The IMO provides the regulatory framework for reducing the pollution rate in maritime transport. The majority of the current international regulations, related to the prevention of pollution in the maritime transport, were drawn in 1973 in the International Convention for the Prevention of Pollution from Ships (MARPOL), which has been subsequently amended three times, as the awareness of the environmental impact of maritime transport has increased. This Convention contains six areas (i.e. annexes), covering different potential pollution sources (IMO 2020): prevention of pollution by oil (Annex I), control of pollution by noxious liquid substances in bulk (Annex II), control of pollution by harmful substances in packaged form (Annex III), prevention of pollution by sewage from ships (Annex IV), prevention of pollution by garbage from ships (Annex V), and prevention of air pollution from ships (Annex VI). Each of these six areas sets forth all the technical requirements and standards to which a shipowner must adhere in order to comply with the international law.

For European Union (EU) member states an additional set of regulation applies. The EU Directive 2005/35/EC enforces the MARPOL framework at the European level and regulates the introduction of penalties for pollution sources, as defined in the first two annexes of the MARPOL. It was amended in 2009 with the Directive 2009/123/EC. Moreover, the Port Reception Facilities (PRF) Directive 200/59/EC strengthens what has been defined in the fifth MARPOL annex, prescribing that all ports shall establish a notification procedure and that all vessels need to report the volumes of waste they intend to deliver, the maximum dedicated storage available, the amount of waste that will be retained on board, the port where the retained waste will be disposed, and the estimated amount of waste to be generated between the two scheduled ports Ospar Commission (2016, p. 13). The Port State Control (PSC) Directive 2013/38/EC defines port inspections of ships sailing under a foreign flag in national ports, ensuring the compliance with the requirements of MARPOL. Penalties can be imposed for non-notification and non-delivery of waste. These are to be charged unless proof of delivery is demonstrated.[4] The administrative Memorandum of Understanding between EU member states, signed in 1982 in Paris, and thus often called Paris MoU, additionally enforces the PSC.[5] The Paris MoU adds more stringent regulations with regard to the safety of shipping, accommodating all the marine requirements set in MARPOL.

In the perspective of the set of countries we analyse in this paper, it is important to highlight that Croatia, Italy, Montenegro, and Slovenia have ratified the whole set of MARPOL regulations. Albania has ratified them all, except of the last (VI) annex that details the prevention of air pollution from ships, while Bosnia and Herzegovina has not ratified any of the texts. This has, however, been expected, given its very small maritime transport and almost non-existent fleet. If the Paris MoU is considered, then it is worth mentioning that Croatia, Italy, and Slovenia are full members; Montenegro is currently a co-operating member, while Albania and Bosnia and Herzegovina do not take part in the agreement.

Moreover, being aware that a serious marine pollution incident may significantly damage, on the one hand the Adriatic ecosystem, and on the other, the economic activities in the region (tourism, fisheries, and energy generation, in particular), in 2005, Croatia, Italy, and Slovenia additionally signed the Agreement on the Sub-Regional Contingency Plan for prevention

4. *For a detailed discussion on sanctions and penalties. refer to Ospar Commission (2016).*
5. *A first version of such administrative agreement, preceding the Paris MoU in 1982, was the "Hague Memorandum" signed in 1978 between Western European countries, which was replaced by Paris MoU.*

of, preparedness for, and response to major marine pollution incidents in the Adriatic Sea.[6]

4. THE THEORETICAL MODEL AND THE ASSESSMENT OF UTILITIES

In the present paper we have taken a game-theoretic approach, in particular, Nash equilibrium analysis, to study the conflict between shipowners whose vessels sail on the Adriatic Sea and countries with coasts on the Adriatic Sea. This approach is preferred over a simple cost-benefit analysis, because it takes into account the strategic nature of the problem. Our simple game-theoretic model involves two interacting parties, namely a shipowner and a country, and incorporates inspections, monitoring, and environmental effects of maritime transport. We have used standard game-theoretic assumptions: (a) interacting parties, henceforth sometimes called players, are rational in the sense they always choose a strategy that maximises their expected utilities, given their knowledge and beliefs about other players' behaviour, and (b) the game, as well as all parameters of the game, i.e. players' available strategies, utilities and outcomes, [7] are common knowledge.[8]

The role of player 1 is taken by a shipowner in charge of a particular type of vessel. To provide more accurate results, we follow van Hammen & van Hammen (2017) and include in our analysis several vessel types with different characteristics. In particular, we consider six main types of standard risk vessels that regularly sail in the Adriatic Sea: a small tanker, a medium tanker, a large tanker, a cruise ship, a Ro-Ro passenger and a fishing vessel. Important to note is that small, medium, and large tankers represent notations that we use for small, medium and large ships that carry any type of cargo, not only oil or chemicals. This means that a small tanker category includes a general cargo, a container ship, a heavy load ship, and a bulk carrier of small size, i.e. up to 1,000 metric tonnes. Similarly, a medium and a large tanker refer to the same set of vessel types but of size from 1000 to 1750 metric tonnes, and above 1,750 metric tonnes, respectively. The role of player 2 is taken by an Adriatic country. We consider six countries that border the Adriatic Sea, i.e. Albania, Bosnia and Herzegovina, Croatia, Italy, Montenegro. and Slovenia.

6. *This Agreement was coordinated by the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC). REMPEC assists the Mediterranean coastal States in ratifying, transposing, implementing. and enforcing international maritime conventions related to the prevention, preparedness. and response to pollution from ships (REMPEC 2020).*
7. *As explained in subsection below, an outcome is a pair of strategies, one for each player.*
8. *Common knowledge was introduced in Lewis (1969). and later studied by Aumann (1976), among others. Intuitively, something is common knowledge if both players know it, both know that both know it, both know that both know that both know it, and so on to infinity.*

While providing transport services, a shipowner (player 1) bears the operating costs. among which also costs for a proper disposal and treatment of waste. Therefore, to save on costs and be more competitive in the industry, a shipowner is often motivated to act in an environmentally unfriendly way (OECD 2003). In that case, lower costs allow the shipowner to provide a larger amount of service for a (lower) price that does not reflect, i.e. cover, all the costs occurring during the provision of transport services. This is a classic example of negative externality on the supply side. One of the main roles of a government (i.e. country or player 2) is to solve such market inefficiencies by monitoring shipowners, assess the marginal external costs of pollution, and define the total costs of service providing, i.e. the marginal social costs (which are just the sum of marginal private and marginal external costs). Obviously, if a shipowner is environmentally friendly, they cover the marginal private costs of proper waste treatment and disposal, and the country has no additional marginal external costs to deal with. However, in the case of shipowner's pollution, the country bears marginal external costs.

To be precise, we introduce two two-player strategic games, henceforth called CIS Pollution game and ABM Pollution game.[9] In both games players are assumed to be risk neutral, and make only one decision, which determines the outcome of the game and final payoffs, called utilities. Players make their decisions simultaneously and confidentially, without knowing what the other player is planning to choose.

The CIS Pollution game concerns countries that are full members of Paris MoU, that is, Croatia, Italy, and Slovenia (Paris MoU, 2020), while the ABM Pollution game involves the rest, i.e. Albania, Bosnia and Herzegovina, and Montenegro. We have decided to analyse the pollution problem separately for members and non-members of Paris MoU, as a consequence of our assumption that members of MoU are more environmentally friendly oriented and conduct inspections more often than non-members. Specifically, we assume that members of Paris MoU care by default, and hence have to choose whether to take comprehensive care of the environment or just normal care, whereas non-members have to decide whether to care or not care at all.

4.1. The CIS Pollution Game

In the role of player 1 is a shipowner who is deciding whether to be environmentally friendly or to pollute the environment (i.e. actions E and P, respectively). An environmentally friendly shipowner bears all pollution costs and/or waste management costs. In the role of player 2 is a country, which decides whether to take comprehensive or normal care for the environment

9. *CIS stands for Croatia, Italy, and Slovenia, while ABM stands for Albania, Bosnia and Herzegovina, and Montenegro.*

(i.e. actions C and N, respectively). The country that takes comprehensive care of the environment uses environmentally friendly technologies, always monitors and inspects vessels, and charges polluters.

As previously explained, if a shipowner is environmentally friendly, they incur waste management costs or additional operating marginal private cost, $C_{mpc} > 0$, regardless of the country's decision and position. In addition, an environmentally friendly shipowner gets benefit B, if a country takes comprehensive care of the environment. We assume that these additional benefits are significant and positive for the shipowner of a fishing vessel ($B = B_f > 0$), and for the shipowner of a cruise ship ($B = B_k > 0$), while the same extra benefits are not relevant for other shipowners (B = 0 otherwise). In particular, a clean environment benefits fishing vessels, since it produces more seafood, and cruise ships, since it attracts more tourists. We assume that a clean environment does not bring extra benefit to other types of vessels, whose profit depends mainly on successful transport of their respective cargo.[10] If a shipowner chooses to pollute the environment and the country takes comprehensive care, the shipowner is inspected and pays a fine F > 0. If a country instead takes normal care, the shipowner is inspected and pays a fine F only with probability μ. In this case, we assume their utility is -μF, which corresponds to the expected fine paid by the polluter.

Comprehensive caring for the environment brings costs $C_c > 0$ to the country, regardless of the shipowner's decision. We assume that these costs include the additional costs of implementing environmentally friendly technologies on all vessels, i.e. costs of replacing old technologies and/or installing new technologies in processing of waters and reduction of air pollution. If a country takes comprehensive care of the environment and a shipowner pollutes it, the country additionally incurs marginal social costs $C_{mpc} > 0$. Marginal social costs represent total costs created while providing for transport services and refer to the sum of marginal private costs and marginal external costs $C_{mec} > 0$. The latter refer to the additional costs generated when the shipowner does not act in an environmentally friendly way and include estimates of subsequently created damage to health, fisheries, tourism, and ecosystem. However, in this case, the country also receives an additional benefit F, i.e. the fine paid by the polluter. If a country takes normal care of the environment, its costs are zero in case the shipowner is environmentally friendly, and C_{msc} otherwise. Also, in the latter case, the country is endowed with additional benefit F with probability μ.

When a country takes normal care of the environment, it does not inspect or monitor vessels all the time, and the shipowner is confronted with a cost-benefit analysis, similar to the one presented in van Hemmen and van Hemmen (2017). If risk of being inspected and/or fined are high, i.e. if the expected fine is high, the shipowner prefers to be environmentally friendly rather than to pollute. When a country takes comprehensive care of the environment, it always catches and sanctions polluters. In this case, a profit-maximising shipowner prefers to be environmentally friendly since this saves money.

When a shipowner acts in an environmentally friendly way, a country opts for normal care, since this does not incur extra costs. When a shipowner pollutes, the country's decision depends on the cost-benefit analysis. In particular, it compares the two payoffs, $-C_c - C_{msc} + F$ and $-C_{msc} + \mu F$, and chooses to take comprehensive care of the environment if the former estimate is higher than the latter. The CIS Pollution game is represented in a bimatrix form, as shown in Table 1.

Table 1.
The CIS Pollution game.

		Country	
		Comprehensive Care	Normal Care
Shipowner	Env. Friendly	$B - C_{mpc}, - C_c$	$- C_{mpc}, 0$
	Pollute	$- F, - C_c - C_{msc} + F$	$-\mu F, -C_{msc} + \mu F$

Note: The rows correspond to shipowner's actions, while the columns correspond to country's actions. In each cell, the first and second numbers correspond to the utilities of shipowner and country, respectively.

10. *Here, it may be argued that a clean environment brings also extra benefit to Ro-Ro passenger ships, given that they also contribute to tourism and transport tourists to different destinations, being more attracted if the environment is preserved. However, given the available data, we are not able to disentangle the transport made by Ro-Ro ships between tourists, passengers for other purposes, and other functions. Moreover, Ro-Ro data include routes that are present throughout the whole year, not only during summer, which is the main (and only) tourist season at the Adriatic. Bearing all this in mind, we prefer to keep our game more conservative and not to add extra benefit to Ro-Ro passenger ships.*

4.2. The ABM Pollution game

In this game variables have the same interpretation and notation as above. In the role of player 1 is a shipowner who is confronted with the same decisions as above. In the role of player 2 is a country which decides whether to care for its environment or not (i.e. actions C and N, respectively). Country that cares for the environment uses environmentally friendly technologies, occasionally monitors and inspects vessels, and charges polluters.

If a shipowner is environmentally friendly, both players get the same utilities as above. If a shipowner instead chooses to pollute the environment, his/her utility corresponds to the expected fine -μF if a country cares for the environment, and 0 otherwise, since it is not going to be inspected at all.

If a country cares for the environment and a shipowner pollutes it, the country receives, in addition to $-C_c - C_{msc}$, an extra benefit corresponding to the expected fine paid by the polluter, μF. If a shipowner pollutes the environment and the country does not solve the pollution problem, the negative impact of pollution (costs) progressively worsens.[11] We assume that the damage increases in a non-linear manner. In particular, we take quadratic marginal external costs and set country's costs to $C_{mpc} + C_{mec}^2$. When a country cares for the environment, the shipowner is confronted with a cost-benefit analysis, similar to the one presented in van Hemmen and van Hemmen (2017). If the risk of being inspected and/or the fine are high, then the shipowner prefers to be environmentally friendly rather than to pollute. When a country does not care about the environment, and thus does not sanction polluters, there is no risk of detection and punishment. In this case a profit-maximising shipowner prefers to pollute since this saves money.

When a shipowner acts environmentally friendly, the country prefers not to care, since it is costless. When a shipowner pollutes, the country prefers to care for the environment, since otherwise the environmental disaster and, consequently, high costs, would be inevitable. The ABM Pollution game is represented in a bimatrix form, as shown in Table 2.

Table 2.
The ABM Pollution game.

		Country	
		Care	Not
Shipowner	Env. Friendly	$B - C_{mpc}, - C_c$	$- C_{mpc}, 0$
	Pollute	$-\mu F, - C_c - C_{msc} + \mu F$	$0, -C_{mpc} - C_{mec}^2$

Note: The rows correspond to shipowner's actions, while the columns correspond to country's actions. In each cell, the first and second numbers correspond to the utilities of shipowner and country, respectively.

4.3. A Game-theoretic Analysis

We have modelled our pollution games as strategic games in which monetary payoffs are considered as cardinal utilities, that is, the values in Tables 1 and 2 not only tell which outcome is better compared to other outcomes, but also by how much. We have analysed our games, using the Nash equilibrium concept (Nash 1950, 1951). Before we proceed, recall that in both games a shipowner's actions are E and P, while the country's actions are C and N. One should have in mind, however, that in the CIS Pollution game C and N correspond to Comprehensive care and Normal care, respectively, while in the ABM Pollution game C and N correspond to Care and Not care, respectively. Since we are interested in Nash equilibrium in mixed strategies, and not only in Nash equilibrium in pure strategies, we have to define our strategy first.

A strategy of a player is a probability distribution that assigns to each player's action a probability of being selected. In particular, for a shipowner, we denote by p the probability of choosing E, and by 1 – p the probability of choosing P. Similarly, for a country, we denote by q the probability of choosing C, and by 1 – q the probability of choosing N. For example, one of the possible strategies of shipowner is to be environmentally friendly with a probability 0.4, and to pollute with a probability 0.6.[12] A strategy that assigns probability 1 to one of the actions is called pure strategy. In the rest of the paper, we ignore the notation when a player chooses the pure strategy, and simply write the action that is played with probability 1. It should be clear from

11. *For example, if an oil spill is not immediately cleaned up, it disperses and can gradually reach the bottom of the sea or even the coast. This could have a potentially negative impact, not only on marine life and ecosystem, but also on human health, fishing industry, and tourism.*
12. *One way to interpret this mixed strategy is the following: before making a decision, a shipowner rolls a 10- sided die, which determines what to choose. If the die shows 4 or less (probability of that is 0.4), the shipowner chooses to be environmentally friendly, otherwise they choose to pollute.*

the context whether a specific letter is being referred to an action or strategy. For example, a shipowner's pure strategy "pollute with probability 1", will be denoted with P, the same as the action pollute. A pair of strategies, one for each player, is called an outcome of the game. For example, in CIS Pollution game one of the possible outcomes is (P, N). It describes the situation in which the shipowner chooses to pollute with probability 1, while the country chooses to take normal care with probability 1.

Intuitively, a Nash equilibrium is an outcome, i.e. a pair of (mixed) strategies, one for each player, such that neither player has an incentive to deviate from their strategy, given the fixed strategy of the other player. It is a steady state of the game. In equilibrium, each player chooses their strategy in a way that makes the other player indifferent between their available actions. A formal mathematical description of Nash equilibrium is given in Appendix D.

It turns out that all our games possess a unique Nash equilibrium. In fact, always one of the following two cases occurs. If one of the players has a strictly dominant action that they prefer to choose, regardless of other player's decision, a game has a unique Nash equilibrium in which both players play pure strategies. If none of the players has a strictly dominant action, then the unique mixed Nash equilibrium exists, and it is calculated using the formulae presented in Table D.1 of Appendix D.

4.4. Assessment of Variables and Calibration of Parameters

In order to study and analyse our pollution games, we estimate a set of variables (B, C_c, C_{mpc}, C_{mec}, C_{msc} and F) and calibrate the parameter μ. The explanations of the approaches given in this subsection are as brief as possible, due to space limitations. However, all details about specific data, amounts and methods are available upon request. Moreover, we provide a systematic view of all variables and parameters needed to assess cardinal utilities and payoffs for the analysis of the game in Table C.1 of Appendix C, while their specific estimation and monetarisation procedures are explained as follows.

To calculate the daily marginal private costs (i.e. costs of proper waste management) per type of vessel, we borrow from the work of Carić (2010), that details on pollution costs of cruise ships, solely.[13] Carić (2010) implements a simple approach; he defines the daily amounts of waste created by an average cruise ship and applies costs of proper waste treatment and disposal, per category of waste, to obtain the total amount of waste management costs. Our analysis, besides cruise ships, includes five more types of vessels: small, medium, and large tankers, fishing vessels and Ro-Ro passenger ships. In order to quantify the daily amounts of waste across different vessel types, we use data about black, grey, bilge, and oily waters shown in Golam Zakaria et al. (2017), assuming that the amount of waste created is equal between inland water transportation and maritime transportation.[14] The daily waste rates per type of waste are used to access the waste management costs per type of vessel. Namely, when a shipowner is environmentally friendly, they also bear these waste management costs, i.e. when in a port, they properly discharge the waste and pay the fees according to the type of waste.

Air pollution costs are difficult to assess on a daily basis. Such costs heavily depend upon distance (usually kilometres) made by a vessel in a day. Given that data about average routes in kilometres per type of vessel for the Adriatic Sea are unavailable, we discard these costs from our analysis for all types of vessels, except the cruise ship. Moreover, cruise ships are those vessels that generate large and significant amounts of air pollution and omitting them in case of these vessels could bias our results.[15] So, to assess these costs we use the amounts of air pollution shown in Transport and Environment (2019) and estimated costs of SO2, NOx and PM emissions set forth in European Commission (2005).

Table A.1 in Appendix A summarises the waste management costs per type of ship and type of waste. If summed, these costs correspond to marginal private costs (Cmpc) a shipowner bears in case they properly treat and dispose waste (these costs are also often referred to as pollution direct costs).

To solve our games, we also need an assessment of the marginal external costs that arise in case the shipowner does not act in the environmentally friendly way and decides to pollute. From the theoretical perspective, these costs include: (1) damage to health, especially of those living on the coastal area; (2) damage to tourism; (3) damage to fisheries; and (4) ecosystem damage (endangered species, ecological status, biodiversity indicators).

Obviously, in order to be comparable to the private waste management costs as estimated in Table A.1, the aforementioned damage (indirect) costs (Cmec) need to be evaluated per ship and per day. Although eventual pollution is a one-time event, its consequences remain for a much longer period. For instance, a large oil spill from the oil tanker generates damages (negative effects) on fisheries, tourism, health, and ecosystem that last for days, months, and even years, depending of the size of the spill.

13. *Cruise ship pollution is also discussed in Carić and Mackelworth (2014) and Carić (2016).*

14. *Golam Zakaria et al. (2017) show that, on a yearly level, a small, medium, and large tanker create a total of waste waters of 50.2, 105.9 and 305 million kg per year, respectively.*

15. *zAmong others, Transport and Environment (2019, p. 2) emphasises that in 2017 Carnival Corporation, the world's largest cruise operator, emitted nearly 10 times more sulphur oxide (SOx) around European coasts than did all 260 million European cars. Ranked second is Royal Caribbean Cruises, the world's second largest operator, that emitted four times more than the overall European car fleet.*

To estimate the damage to health we use UNCTAD (2020) and European Commission (2005) data. On the one hand, UNCTAD (2020) allows us to calculate world annual average emissions of SO2, NOx and PM across types of vessels in tonnes. On the other hand, European Commission (2005) estimates average health costs per ton emission of SO2, NOx and PM in the Mediterranean Sea amounting to 3,775. 920 and 10,325 euro, respectively.[16]

Estimating the damage to tourism and fisheries is more particular and country specific, unlike the damage to health, which we assume being identical in all countries under the assumption that health of any individual, no matter of their residence, is equally worth. We proxy the benefits of tourism per day per country using number of nights spent at tourist accommodations along the Adriatic coast per country.[17] In case of an environmentally unfriendly shipowner, these daily values represent the losses a country is facing given the pollution created by illegal discharges or oil spills. In case of the damage to fisheries, we use and elaborate FAO's data about fishing fleet, landing values and employment in the fishing industry FAO (2018, p. 5, 9 and 94), which enables us to estimate the value of landing per country, per fishing vessel per day. Given the availability of employment data in the fishing industry, we also account for the effects of a reduction in employment that occurs after pollution is not treated. In our baseline estimates, we assume a reduction in employment of five percent on a yearly level. FAO (2018) indicates that employment levels in the fishing industries grow around ten percent on a yearly basis. Therefore, our specified level of reduction of five percent assumes that, after pollution occurs, the fishing industry will grow on a lower pace, i.e. half of the average. We find this estimate quite conservative, given that a more realistic scenario would imply stagnation (no growth at all) at most, rather than any growth. Applying the latter would only reinforce our results.

There exist a number of indicators that account for the state of the maritime ecosystem. Most of them are quite difficult to monetarise and evaluate (e.g. growth of harmful algae blooms). [18] However, in order to account for at least a small portion of the ecosystem damage, we rely on the most growing marine problem, i.e. marine plastics. Beaumont et al. (2019) estimate that marine plastic costs the world 2,25 trillion euro per year. We use the surface data (in km2) to proxy for the costs of marine plastics in the Adriatic Sea. Then, we redefine such estimate as a per day per vessel value. Although the shares of the territorial Adriatic Sea are different among the six countries in our analysis, we assume that the damage per vessel is on average equal across countries. This is so due to the fact that more plastic garbage disposed illegally in Bosnian waters can easily be brought by currents elsewhere (Italy, for example).

Table B.1 in Appendix B gives a comprehensive overview of all the estimates of marginal external costs per category of damage and type of vessel, that a country incurs, after an improper treatment and disposal of waste, while Table C.1 summarises monetarised values for total marginal external costs per type of vessel and country. The same table also shows specific values of marginal social costs, as the sum of marginal private costs and marginal external costs.

Additional variables that need to be accounted for are country's benefits, B, country's costs, C_c, and fines, F. As pointed in Section 4, in case the most environmentally friendly outcome is realised, i.e. the outcome (E, C), the fishing industry (fishing vessel), and tourism (cruise ship) account for additional benefits. To monetarise such benefits we assume that these sectors will grow in the future at constant rates, proxied by their respective average growth rates in the observed 2010-2018. Therefore we suppose that the average values of travel credits in the balance of payment, as well as fish landing, will grow at a constant rate in the future. This is similar to assuming a perpetuity of the benefits with no end, which allows us to borrow from the concept of consoles that in finances correspond to a fixed-income security with no maturity date (i.e. fixed income lasts forever).[19] We discount the benefits using the 2% discount rate and set the annual amount to daily levels.[20] The costs of implementing new or replacing old technologies to achieve the highest standard and lowest pollution levels of ships (C_c) is retrieved relying on European Commission (2013). The latter report details on typical emissions across different vessel types and sets average costs needed

16. *The same costs of emissions on a country level, such as Italy or Slovenia, are much larger if disposed in mainland where other air pollution (industry, other forms of traffic) occurs as well.*
17. *We are aware of the presence of the tourism multiplier, and that benefits of tourism are reflected in many accompanying activities and go beyond the values expressed in the balance of payments. Regardless of that, we prefer to keep our estimates conservative. Applying the multiplier, and/or including additional benefits would only reinforce our results.*
18. *Like for example the introduction and growth of marine non-indigenous species, inspection of hazardous substances in marine organisms or fish and shellfish stocks, or plastic pollution.*
19. *A consol, or perpetual bond, is often considered equity (capital), rather than debt (Cecchetti and Schoenholtz 2015, among others). The present value of such bond is just the ratio between fixed payments and a discount rate. The latter reduces the real value of nominal fixed payments over time, making the value equal to zero. So, although consols pay nominal payments forever, they can be assigned a finite value. For example, if a consol pays 1,000 monetary units per year and the discount rate is 4%, then the present value of that consol is 25,000 monetary units (1,000/0.04).*
20. *Drupp et al. (2018) survey around 200 economists to find the median social discount rate used in different cost benefit analysis. They find that the median social discount rate stands at 2%. This is lower than a median discount rate used in assessing financial present values of future cashflow by private companies. Using a low discount rate increases the present value of future cash inflow or outflow and supports the view that acting today protects future generations. This is perfectly in line with our pollution games, where if a shipowner pollutes, they create a burden (less benefits) for future generations.*

to achieve the reduction in air pollutants. As in case of health damage, we assume equality of such costs across countries, although we are aware of price differentials, as well as of their distinctive fleet characteristics.

Specific values for fines paid by ships in the Adriatic Sea are unavailable but can be proxied by average European fines expressed in Ospar Commission (2016). The latter work gives a comprehensive assessment of fines and sanctions issued after inspections questing the MARPOL pollution requirements for a set of Northern European countries. These countries, from the Ospar Commission (2016) dataset, are also EU member states and comply with the same set of rules and regulations (as explained in Section 3) as member and accessing EU countries of our dataset. Therefore, we assume that if the same pollution violations were found in the Adriatic Sea, on average, similar fines, as well as similar detentions, would have been applied. Given the difficulty to monetarise detentions, we have left them out of our analysis. According to Ospar Commission (2016, p. 19-20) the 189 illegal discharges made by national vessels (port state) are on average fined 11,192 euro, while the 241 illegal discharges made by foreign vessels (flag state) are on average fined 3,136 euro. The weighted average fine for all vessels (independent of their flag state) amounts to 6,677 euro, and we apply that in case of vessels that fall into the M tanker category, while for S and L tanker categories we scale it using the ratios $C_{mpc}^{S}/C_{mpc}^{M} = 0.477$ and $C_{mpc}^{L}/C_{mpc}^{M} = 2.817$, respectively. This way of scaling, i.e. based on marginal private costs, is two-fold. On the one hand, marginal private costs reflect costs of adequate treatment and disposal of waste, i.e. costs if the shipowner does not pollute. This means that using those to construct scaling factors allows us to assume that the fine is proportional to the amount of generated waste. On the other hand, such scaling also ensures that a critical value of μ, at which the shipowner of the tanker is indifferent between E and P, is the same for all types of tankers. In case of cruise ships, the same fines are usually much larger.[21] So, assuming that cruise ships are more heavily fined, we calibrate the value using the average of maximum fines reported in Ospar Commission (2016), which amounts to 109,895 euro. As regarding fishing vessels and Ro-Ro ships, we calibrate the fine to 274 and 822 euro, respectively. Namely, the Croatian law establishes the lower bound for fines in case of fishing vessels to 274 euro. Assuming that a Ro-Ro ship is on average at least 3 times larger, we set the corresponding fine to 822 euro. Given that we work with lower bounds, our estimates are quite conservative in this case as well.

Last but not least, we calibrate the probability of being inspected, μ. We first estimate μ for members of Paris MoU. To do so we rely on Equasis statistics, more specifically, on Equasis (2019, p. 70, Table 111). For each tanker category, we estimate μ by calculating the weighted average of all the eleven cargo ships listed in Equasis statistics (Ro-Ro cargo excluded). Our estimates for μ result in 2.4%, 56.1% and 91.1% for the S, M and L tanker category, respectively. For cruise ships, we compute the weighted average of Large and Very Large Passenger Ship categories, and set μ to 97.2%. Similarly, referring to the data for the Small Other category, we set μ for fishing vessels equal to 3.9%, while μ for Ro-Ro passenger ships amounts to 7.9%, obtained as the weighted average of Small and Medium Ro- Ro Passenger Ship. Next, we turn to non-members of Paris MoU. Since Montenegro is a co-operating member of Paris MoU, and may become a full member in the future, we assume it strives to accomplish the objectives of Paris MoU, and hence sets their inspection rates at the same level as that of Paris MoU members. For Albania and Bosnia and Herzegovina specific inspection data on a national basis is unavailable. Hence, we opt to scale the estimated values of μ. The Albanian flag is on the Paris MoU blacklist (Paris MoU 2020), and hence we assume it is not performing well. For Bosnia and Herzegovina, we assume that its narrow access to the sea and almost non-existent fleet do not generate enough incentives to tackle marine environmental problems at all. Therefore, to determine the scalars, we use the country's respective coast length shares in the total Adriatic coast, and obtain 0.08 for Albania and 0.01 for Bosnia and Herzegovina.[22] Moreover, for Bosnia and Herzegovina, we estimate μ only for fishing vessels, since Bosnian port in Neum is currently not suitable for larger vessels.

5. DISCUSSION OF RESULTS

This section presents the results of Nash equilibrium analysis. Nash equilibria are obtained by first plugging estimates into Table 1 or 2, and then using the definition of Nash equilibrium. In particular, mixed Nash equilibria are calculated from Table D.1, which is based on equations (D.1) and (D.2); see Appendix D. Each game has only one Nash equilibrium and a brief overview of these are shown in Table 3. In Table 3, the explicit Nash equilibrium is given for games in which Nash

21. *For example, the cruise ship Regal Princess was fined half a million of USD in 1993 for discharging 20 bags of garbage in the sea (Ospar Commission 2016). The same line of cruisers, yet sailing under the Carnival group, in 2016 was fined 40 million USD along with a five-year probation for dumping waste in the sea, and re-fined with additional 20 million USD after re-committing the act during the probation period (Allen 2019).*

22. *Our estimates rely on Simeoni et al. (1997) and Zonn and Kostianoy (2016). In particular, for all countries, except Albania, we assume the coastal lengths reported in Zonn and Kostianoy (2016). For Albania we take the coastal length reported in Simeoni et al. (1997), according to which only about 284 km – not 362 km, as written in Zonn and Kostianoy (2016) – belong to the Adriatic part (the rest belongs to the Ionian). It is worth mentioning that the literature is not unanimous regarding the Adriatic coastal lengths of each country, and hence estimates could be slightly different using other literature. It is important to emphasise, however, that even if the length of 362 km is used instead, the conclusions remain robust.*

equilibrium consists of pure strategies, while "mix" is written for games in which Nash equilibrium consists of mixed strategies. In the case of Bosnia and Herzegovina we study only one game due to the reasons outlined above, and write "/" for unanalysed cases. Each cell in Table 3 corresponds to one game, for example, the cell in the third row and second column corresponds to the CIS Pollution game between a shipowner that oversees a large (L) tanker and Italy. The entry (E, N) in this cell tells that the game in question has one Nash equilibrium in which the shipowner chooses to be environmentally friendly with probability 1, and Italy chooses to take normal care with probability 1.

Table 3.
Mixed Nash Equilibria.

	HR	IT	SI	ME	AL	BA
S tanker	mix	mix	mix	(P, C)	(P, C)	/
M tanker	(E, N)	(E, N)	(E, N)	mix	(P, C)	/
L tanker	(E, N)	(E, N)	(E, N)	mix	(P, C)	/
Cruise ship	(E, N)	(E, N)	(E, N)	mix	mix	/
Fishing vessel	mix	mix	mix	(P, C)	(P, C)	(P, C)
Ro-Ro	mix	mix	mix	(P, C)	(P, C)	/

Table 4.
Mixed Nash Equilibria – Croatia, Italy and Slovenia.

	HR	IT	SI
S tanker	p=0.977 q=0.098	p=0.977 q=0.098	p=0.977 q=0.098
Fishing vessel	p=0.985 q=0.165	p=0.985 q=0.097	p=0.985 q=0.140
Ro-Ro	p=0.987 q=0.042	p=0.987 q=0.042	p=0.987 q=0.042

We begin a more detailed description of results with members of Paris MoU, namely Croatia, Italy, and Slovenia, who play the CIS Pollution game. In all three countries, when a shipowner oversees a medium tanker, large tanker or cruise ship, fines and probability of being inspected are high enough to prevent shipowners from polluting, regardless of the country's decision.[23] Since each of these three countries prefers to take normal care, when shipowner does not pollute, it follows that the game has one Nash equilibrium, namely (E, N). Therefore, in this case, the game theory predicts that shipowners of these vessels are environmentally friendly and the country takes normal care. For the other three types of vessels, i.e. small tanker, fishing vessel, and Ro-Ro passenger ship, expected fines are too low to prevent shipowners from polluting when the country takes normal care. This leads to unique mixed Nash equilibrium, in which the shipowner of a particular vessel chooses n environmentally friendly action with a probability p, and the country chooses to take comprehensive care with a probability q, where p and q for a specific vessel and country are given in Table 4. [24]

For each of the three vessel types in Table 4, values of p, i.e. the probability of acting environmentally friendly, are identical in all three countries, and higher than 97.5%, regardless of the vessel type. High values of p suggest that shipowners of small tanker, fishing vessel, and Ro-Ro passenger ship in general also act environmentally friendly. Reason for that are costs C_c, which are relatively low compared to $(1-\mu)F$, which is one of the terms that determines p (see the upper left cell of Table 9. in Appendix D). If p were lower, i.e. if shipowners choose to pollute more often, the countries would take comprehensive care with probability 1, and players would not be in equilibrium anymore.

23. In other words, action E is strictly dominant.

24. All values in Tables 4 and 5 are rounded up to three decimal places.

For each of the three countries in Table 4, in case of S tanker and Ro-Ro passenger ship, values of q, i.e. the probability of taking a comprehensive care, are identical in all three countries, and lower than 10%. If q were higher, shipowners would act in an environmentally friendly way, with a probability 1, and players would be out of equilibrium.[25] Our game-theoretic model therefore suggests that, in general, Adriatic countries do not take extra care of the environment. Similar interpretation also holds for fishing vessels, although in this case values of q vary slightly between countries. These differences arise due to the estimated benefits B, which are highest in Italy and lowest in Croatia. From the country's perspective, the higher value of B makes shipowner's action E more attractive and, consequently, the country's action C less attractive. In other words, q decreases if B increases.

The non-members of Paris MoU, i.e. Albania, Bosnia and Herzegovina, and Montenegro, play the ABM Pollution game. In the case of Bosnia and Herzegovina we have analysed only fishing vessels due to all the aforementioned reasons. Our game-theoretic analysis suggests that due to the low value of μ, a shipowner is always better off by polluting, regardless of the country's decision, i.e. action P is strictly dominant. Since Bosnia and Herzegovina prefers to take care when the shipowner pollutes, it follows that the game has one Nash equilibrium, namely (P,C). Hence, for Bosnia and Herzegovina game theory predicts that shipowners pollute and the country takes care. Regarding Albania, the same conclusions hold in all cases except when a shipowner is in charge of a cruise ship, while for Montenegro (P,C) it is predicted in case of a small tanker, a fishing vessel and a Ro-Ro passenger ship. In each of these cases the expected fines are too low to deter shipowners from polluting. Moreover, in case of Albania, whenever a shipowner is in charge of a cruise ship, they and the country play mixed strategies, and the most probable outcome to happen is (E,N). The values of p and q, rounded up to three decimal places, are 0.998 and 0.302, respectively. A probability p close to 1 means that a shipowner almost always acts environmentally friendly,[26] while probability q close to 0.3 means that a country takes care only occasionally.

In the case of Montenegro, game theory predicts shipowner and country play the mixed strategies whenever a shipowner is in charge of a medium tanker, large tanker, or cruise ship. In each of these cases the most probable outcome to be realised is (E,N). Values of p and q are shown in Table 5. As in the Albanian case, in mixed Nash equilibrium shipowners choose E with a probability close to 1. Intuitively, for Montenegro the estimated inspections rates, μ, and consequently expected fines, are high enough to reduce pollution, which allows it to take care only occasionally in case of tankers, and almost never in case of cruise ship.

Table 5.
Mixed Nash Equilibria – Montenegro.

	ME
M tanker	p=0.999, q=0.213
L tanker	p=0.999, q=0.131
Cruise ship	p=0.999, q=0.024

As a final comment, we return to one of our statements that we have made in Subsection 4.1, namely "When a country takes comprehensive care of the environment, it always catches and sanctions polluters. In this case a profit-maximising shipowner prefers to be environmentally friendly since this saves money." As one of the anonymous reviewers pointed out, this is debatable, as practice shows that some keep polluting even in countries that take extensive care and even after they have already been fined (Allen 2019). Since in real life countries almost never inspect all the ships, comprehensive care can be interpreted as more or less an "ideal" situation in which a country could and would inspect everyone. The extensive care that some countries take is in our model thus seen more as the example of a normal care where probability of inspection is very high (e.g. for cruise ships is around 97% in the strictest countries), but below 100% (Equasis 2019, p.70, Table 111). Indeed, as our game-theoretic analysis has demonstrated, the strictest Paris MoU countries will never choose comprehensive care with a probability 1, because it is not an equilibrium action (it is only a feasible action). Namely, if a country took comprehensive care, a potential polluter would know that they would definitely get caught and fined, and therefore would not pollute. But if that is the case, the country would not need to take comprehensive care, as it is more costly than normal care, implying that comprehensive care is not an equilibrium action.

Having said this, we propose three possible explanations why the acts of pollution are still observed in practice, even if inspection rates are high. One possible reason is simply that shipowners are risk loving, which, in the language of mathematics, means that their utility do not change in a linear manner. Another reason may lie in the fact that they are unaware of the seriousness of their violations, the size of the resulting penalties or the strategies that the country can take, which in game-theoretic sense means that some parameters of the game, or even the game itself, is not a common knowledge. The third, and our final possible explanation,u comes from the behavioural literature, namely from Kahneman and Tversky (1979) observation that in

25. *For example, if a country randomly chooses an action (i.e. if a country uses the mixed strategy that assigns probability 1/2 to each of its actions), and shipowner chooses pure strategy E, which is a best response to country's mixed strategy, country has an incentive to deviate to pure strategy N. But the profitable deviation of at least one player means the outcome in question is not an equilibrium.*
26. *The main reason for this is a huge cruise ship fine that shipowner must pay if they get caught polluting.*

risky situations people do not perceive high probabilities as they are but underestimate them (e.g., they perceive 95% as 80%). If that is the case, shipowners may believe that the expected fines are actually much smaller, and hence may pollute with a higher probability.

6. CONCLUSION

This study assesses the efficiency of MARPOL regulation in preventing and controlling maritime pollution, using the Adriatic Sea case. Having in mind the importance of economic activities linked to the Adriatic Sea (tourism, transport, and fisheries at most), and the high likelihood of pollution by marine vessels that regularly transport passengers and cargo along its routes, we inspect the behaviour of shipowners, guided by the maximisation of profits, and countries, guided by societal interests, in safeguarding the environment using a game-theoretic approach.

We show that MARPOL is efficient if coupled with Paris MoU, given that inspection rates and expected fines are generally high enough to prevent shipowners from polluting. Our analysis also indicates that in the countries where monitoring and controlling are less frequent and intensive (as in case of non-members of Paris MoU), the expected fines are generally too low to motivate shipowners of smaller vessels to behave in environmentally friendly ways. Therefore, the set of current marine pollution regulation (MARPOL along with EU Directives and Paris MoU), if strictly implemented, is efficient in preventing shipowners from illegal discharges, and safeguards the marine environment. From the policy perspective, this highlights the fact that stronger intra-governmental cooperation is needed to protect the environment and reach a sustainable growth level. Individual (country) actions in safeguarding the marine environment, no matter how strong and ambitious they are, may not be enough, if hindered by neighbouring countries that do not follow the same strategy and do not aim at the same sustainable goal. This means that national governments alone cannot properly tackle global marine environmental issues, which is in line with the current literature focusing on other global actions, such as climate change or transboundary pollution in general. As a final note, our findings suggest that in situations where shipowners are more inclined towards green strategies, countries are more likely to choose less costly but also less environmentally friendly options, which is not the most promising scenario for our environment and sustainable growth.

Our findings also point to relevant paths for future research. First, we have shown more knowledge on the efficiency of MARPOL with respect to all pollution sources and across six types of vessels. While this paper sets out to identify if countries care or do not care how shipowners act regarding waste treatment and oil pollution, we recognise that additional theoretical and empirical work should be employed in modelling different cooperation levels across countries in tackling this global problem. Second, we are confident that our comprehensive set of empirical estimates presents relevant essentials for future research in marine pollution, as well as for other transboundary pollution problems. Third, specific attention should be devoted to testing efficient inspection rates, fines and policy actions that would motivate countries to take more environmentally friendly actions. This is especially relevant from the EU perspective, where funds from the EU budget can be specifically devoted in targeting more environmentally friendly policies in member and accessing countries. Therefore, future research could even investigate which of the strategies, stick or carrot, would provide more motivation and work better.

CONFLICT OF INTEREST

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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REFERENCES

Ahlvik, L. & Pavlova, Y., 2013. A Strategic Analysis of Eutrophication Abatement in the Baltic Sea. Environmental and Resource Economics, 56(3), pp.353–378. Available at: http://dx.doi.org/10.1007/s10640-013-9651-1.

Allen, G., 2019. Carnival Cruise Lines Hit With $ 20 Million Penalty For Environmental Crimes. Newspaper article from June 4, 2019. Available at: www.npr.org.

Aumann, R.J., 1976. Agreeing to Disagree. The Annals of Statistics, 4(6). Available at: http://dx.doi.org/10.1214/aos/1176343654.

Bachér, H. and Albrecht, P., 2013. Evaluating the costs arising from new maritime environmental regulations. Trafi publications, 24.

Bayramoglu, B., 2006. Transboundary Pollution in the Black Sea: Comparison of Institutional Arrangements. Environmental and Resource Economics, 35(4), pp.289–325. Available at: http://dx.doi.org/10.1007/s10640-006-9016-0.

Beaumont, N.J. et al., 2019. Global ecological, social and economic impacts of marine plastic. Marine Pollution Bulletin, 142, pp.189–195. Available at: http://dx.doi.org/10.1016/j.marpolbul.2019.03.022.

Bureau of Transportation Statistics, 2020. Official web page of the Bureau of Transportation Statistics, Department of Transportation, Summary of Cruise Ship Waste Streams. Available at: https://www.bts.dot.gov/bts/bts/archive/publications/maritime_ trade_and_transportation/2002/environmental_issues_table_01.

Carić, H., 2016. Challenges and prospects of valuation – cruise ship pollution case. Journal of Cleaner Production, 111, pp.487–498. Available at: http://dx.doi.org/10.1016/j.jclepro.2015.01.033.

Carić, H., 2010. Direct pollution cost assessment of cruising tourism in the Croatian Adriatic. Financial Theory and Practice, 34(2), pp. 161–180.

Carić, H. & Mackelworth, P., 2014. Cruise tourism environmental impacts – The perspective from the Adriatic Sea. Ocean & Coastal Management, 102, pp.350–363. Available at: http://dx.doi.org/10.1016/j.ocecoaman.2014.09.008.

Cecchetti, S.G. and Schoenholtz, K.L., 2015. Money, Banking and Financial Markets - Fourth Edition. McGraw-Hill Education, New York.

Dinar, A. & Hogarth, M., 2015. Game Theory and Water Resources Critical Review of its Contributions, Progress and Remaining Challenges. Foundations and Trends® in Microeconomics, 11(1-2), pp.1–139. Available at: http://dx.doi.org/10.1561/0700000066.

Drupp, M.A. et al., 2018. Discounting Disentangled. American Economic Journal: Economic Policy, 10(4), pp.109–134. Available at: http://dx.doi.org/10.1257/pol.20160240.

Equasis, 2019. The World Merchant Fleet in 2018. Available at: http://www.equasis.org/Fichiers/Statistique/MOA/Documents%20availables%20on%20statistics%20of%20Equasis/Equasis%20Statistics%20-%20The%20world%20fleet%202018.pdf.

European Commission, 2005. Damages per tonne emission of PM2.5, NH3, SO2, NOx and VOCs from each EU25 Member State (excluding Cyprus) and surrounding seas, European Commission DG Environment, Available at: https://ec.europa.eu/environment/archives/cafe/activities/pdf/cafe_cba_externalities.pdf.

European Commission, 2013. EU Ship Emissions to Air Study - Appendix 5, European Commission DG Environment. Available at: https://ec.europa.eu/environment/enveco/taxation/ship_emissions/pdf/app5final.pdf.

European Commission, 2018. Future brief: What are the health costs of environmental pollution?, European Commission Science for Environment Policy 21, Available at: https://doi.org/10.2779/733278.

European Environment Agency, 2007. Europe's Environment-the Fourth Assessment. European Environment Agency, Copenhagen.

European Environment Agency, 2020. Towards a cleaner Mediterranean: a decade of progress. EEA Report 07/2020, European Environment Agency, Luxembourg. Available at: https://doi.org/10.2800/623712.

Eurostat, 2020. The official web page of the European Commission Eurostat statistics. Available at: https://ec.europa.eu/eurostat/home.

FAO, 2018. The State of Mediterranean and Black Sea Fisheries. General Fisheries Commission for the Mediterranean, Italy: Rome.

Fernandez, L., 2002. Trade's Dynamic Solutions to Transboundary Pollution. Journal of Environmental Economics and Management, 43(3), pp. 386–411. Available at: https://doi.org/10.1006/jeem.2001.1187.

Zakaria, N.M.G., Rashid, K. & Khaled, M.I., 2017. Environmental Pollution in Bangladesh by Inland Tanker Operation. Procedia Engineering, 194, pp.330–336. Available at: http://dx.doi.org/10.1016/j.proeng.2017.08.153.

Hay, J., 2009. How efficient can international compensation regimes be in pollution prevention? A discussion of the case of marine oil spills. International Environmental Agreements: Politics, Law and Economics, 10(1), pp.29–44. Available at: http://dx.doi.org/10.1007/s10784-009-9096-8.

IMO, 2020. The official web page of the International Maritime Organization. Available at: www.imo.org.

ISPRA, 2022. Monitoraggio strategia marina – rifiuti marini spiaggiati. Available at: https://annuario.isprambiente.it/sys_ind/631.

Kahneman, D. & Tversky, A., 1979. Prospect Theory: An Analysis of Decision under Risk. Econometrica, 47(2), p.263. Available at: http://dx.doi.org/10.2307/1914185.

Lewis, D., 1969. Convention: a philosophical study. Harvard University Press, Cambridge, MA.

Li, K.X. & Tapiero, C.S., 2010. Strategic Naval Inspection for Port Safety and Security. SSRN Electronic Journal. Available at: http://dx.doi.org/10.2139/ssrn.1732290.

Madani, K., 2010. Game theory and water resources. Journal of Hydrology, 381(3-4), pp.225–238. Available at: http://dx.doi.org/10.1016/j.jhydrol.2009.11.045.

Morović, M. et al., 2015. Oil spills distribution in the Middle and Southern Adriatic Sea as a result of intensive ship traffic. Acta Adriatica, 56(2), pp. 145 –156.

Nash, J.F., 1950. Equilibrium points in n-person games. Proceedings of the National Academy of Sciences, 36(1), pp.48–49. Available at: http://dx.doi.org/10.1073/pnas.36.1.48.

Nash, J., 1951. Non-Cooperative Games. The Annals of Mathematics, 54(2), p.286. Available at: http://dx.doi.org/10.2307/1969529.

OECD, 2003. Cost savings stemming from non-compliance with international environmental regulations in the maritime sector. OECD: Paris.

Ospar Commission, 2016. Sanctions, penalties and fines issued by OSPAR and HELCOM Contracting Parties for waste disposal offences at sea.

Paris MoU, 2019. Port State Control Consistent Compliance - Annual report 2018. Available at: https://www.parismou.org/system/files/2018%20Annual%20Paris%20MoU.pdf.

Paris MoU, 2020. Official web page of the Paris Memorandum of Understanding on Port State Control, Available at: www.parismou.org.

REMPEC, 2020. Official web page of the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea. Available at: www.rempec.org.

Simeoni, U., Pano, N. and Ciavola, P., 1997. The coastline of Albania: morphology, evolution and coastal management issues. In Transformations and evolution of the Mediterranean coastline, CIESM Science Series Volume 3, Bulletin de l'Institut Océanographique de Monaco, Special Issue 18, pp. 151–168.

Transport and Environment, 2019. One Corporation to Pollute Them All: Luxury cruise air emissions in Europe. European Federation for Transport and Environment, Belgium: Brussels.

UNCTAD, 2020. The official web page of the United Nations Conference on Trade and Development statistics, Available at: https://unctadstat.unctad.org.

van Hemmen, H., and van Hemmen, H.F., 2017. Cost Analysis of Compliance with MARPOL Annex I OWS Regulations. The Society of Naval Architects and Marine Engineers. Available at: https://martinottaway.com/wp-content/uploads/2017/08/MAX1-Cost-Analysis-Report-April-26-2017.pdf.

Wei, S. & Gnauck, A., 2007. Simulating water conflicts using game theoretical models for water resources management. Ecosytems and Sustainable Development VI. Available at: http://dx.doi.org/10.2495/eco070011.

Yang, Zhisen et al., 2018. A risk-based game model for rational inspections in port state control. Transportation Research Part E: Logistics and Transportation Review, 118, pp.477–495. Available at: http://dx.doi.org/10.1016/j.tre.2018.08.001.

Yu, S. et al., 2017. Nash bargaining solutions for international climate agreements under different sets of bargaining weights. International Environmental Agreements: Politics, Law and Economics, 17(5), pp.709–729. Available at: http://dx.doi.org/10.1007/s10784-017-9351-3.

Zonn I.S., Kostianoy, A.G., 2016. The Adriatic Sea. In The Boka Kotorska Bay Environment. The Handbook of Environmental Chemistry 54. Springer.

APPENDIX A.
Marginal Private Costs of Proper Waste Treatment and Disposal Per Type of Vessel

Table 6.
Daily waste management costs per type of vessel and type of waste in euro.

	S tanker	M tanker	L tanker	Cruise ship	Fishing v.	Ro-Ro
Air pollution	n.a.	n.a.	n.a.	933.70	n.a.	n.a.
Solid waste	2.74	5.02	5.70	65.14	0.21	1.14
Other waters*	364.47	768.86	2216.56	35.96	54.67	91.12
Grey waters	1.81	19.82	22.52	1438.57	0.81	2.70
Hazardous waste	2.94	5.39	6.12	109.29	0.22	1.22
Total	380.95	799.09	2250.91	2582.66	55.91	96.18

*Notes: * Other waters include bilge, black and ballast waters. S, M and L stand for small, medium and large, respectively. A small tanker category represents a general cargo, a container ship, a heavy load ship and a bulk carrier of small size, i.e. up to 1,000 metric tons. Similarly, a medium and a large tanker refer to the same set of vessel types but of size from 1,000 to 1,750 metric tonnes, and above 1,750 metric tonnes, respectively.*

APPENDIX B.
Marginal External Pollution Costs Per Type of Vessel and Country

Table 7.
Daily marginal external costs per type of vessel and country along different dimensions of damage in euro.

	AL	BA	HR	IT	ME	SI
				S tanker		
Health	47.32	47.32	47.32	47.32	47.32	47.32
Tourism	22.32	14.00	114.17	193.30	229.18	177.80
Fisheries	106.81	0.00	23.44	68.92	21.94	33.57
Ecosystem	7.81	7.81	7.81	7.81	7.81	7.81
Total	184.25	69.14	192.74	317.36	306.26	266.52
				M tanker		
Health	117.01	117.01	117.01	117.01	117.01	117.01
Tourism	122.31	14.00	114.17	193.30	229.18	177.80
Fisheries	106.81	0.00	23.44	68.92	21.94	33.57
Ecosystem	7.81	7.81	7.81	7.81	7.81	7.81
Total	353.94	138.82	262.42	387.04	375.94	336.20
				L tanker		
Health	185.79	185.79	185.79	185.79	185.79	185.79
Tourism	122.31	14.00	114.17	193.30	229.18	177.80
Fisheries	106.81	0.00	23.44	68.92	21.94	33.57
Ecosystem	7.81	7.81	7.81	7.81	7.81	7.81
Total	422.73	207.61	331.21	455.83	444.73	404.99

			Cruise ship			
Health	213.66	213.66	213.66	213.66	213.66	213.66
Tourism	140.65	14.00	131.29	222.29	263.55	204.47
Fisheries	122.83	0.00	26.95	79.26	25.23	38.61
Ecosystem	8.99	8.99	8.99	8.99	8.99	8.99
Total	486.13	236.65	380.89	524.21	511.44	465.73
			Fishing vessel			
Health	7.10	7.10	7.10	7.10	7.10	7.10
Tourism	3.35	2.10	17.12	28.99	34.38	26.67
Fisheries	16.02	0.00	3.52	10.34	3.29	5.04
Ecosystem	1.17	1.17	1.17	1.17	1.17	1.17
Total	27.64	10.37	28.91	47.60	45.94	39.98
			Ro-Ro ship			
Health	26.64	26.64	26.64	26.64	26.64	26.64
Tourism	5.58	3.50	28.54	48.32	57.29	44.45
Fisheries	26.70	0.00	5.86	17.23	5.49	8.39
Ecosystem	1.95	1.95	1.95	1.95	1.95	1.95
Total	60.87	32.09	62.99	94.15	91.37	81.44

Notes: S, M and L stand for small, medium and large, respectively. A small tanker category represents a general cargo, a container ship, a heavy load ship and a bulk carrier of small size, i.e. up to 1,000 metric tons. Similarly, a medium and a large tanker refer to the same set of vessel types but of size from 1,000 to 1,750 metric tonnes, and above 1,750 metric tonnes, respectively.

APPENDIX C.
Summary of All Estimates Used in the Game-theoretic Analysis

Table 8.
Summary of parameters, estimated values per ship and per country for model variables in EUR.

			Player 1 (shipowner)			
	S tanker	M tanker	L tanker	Cruise ship	Fishing v.	Ro-Ro
C_{mpc}	380.95	799.09	2250.91	2582.66	55.91	96.18
F	3183.00	6677.00	18808.00	109895.00	274.00	822.00
B – AL	0	0	0	20.83	33.62	0
B – BA	0	0	0	0	0	0
B – HR	0	0	0	58.76	10.82	0
B – ME	0	0	0	220.39	201.50	0
B – IT	0	0	0	7.86	40.44	0
B – SI	0	0	0	12.19	60.32	0
			Player 2 (country)			
	AL	BA	HR	IT	ME	SI
C_mec – S tanker	184.25	69.14	192.74	317.36	306.26	266.52

C_mec – M tanker	353.94	138.82	262.42	387.04	375.94	336.20
C_mec – L tanker	422.73	207.61	331.21	455.83	444.73	404.99
C_mec – Cruise ship	486.13	236.65	380.89	524.20	511.44	465.73
C_mec – Fishing v.	42.64	10.37	28.91	47.60	45.94	39.98
C_mec – Ro-Ro	85.87	32.09	62.99	94.15	91.37	81.44
C_msc – S tanker	565.20	450.09	573.69	698.31	687.21	647.47
C_msc – M tanker	1153.03	937.91	1061.51	1186.13	1175.03	1135.29
C_msc – L tanker	2673.64	2458.52	2582.12	2706.74	2695.64	2655.90
C_msc – Cruise ship	3068.79	2819.31	2963.55	3106.86	3094.10	3048.39
C_msc – Fishing v.	98.55	66.28	84.82	103.51	101.85	95.89
C_msc – Ro-Ro	182.05	128.27	159.17	190.33	187.55	177.62
C_c – S tanker	72.85	72.85	72.85	72.85	72.85	72.85
C_c – M tanker	95.40	95.40	95.40	95.40	95.40	95.40
C_c – L tanker	158.50	158.50	158.50	158.50	158.50	158.50
C_c – Cruise ship	456.20	456.20	456.20	456.20	456.20	456.20
C_c – Fishing v.	4.08	4.08	4.08	4.08	4.08	4.08
C_c – Ro-Ro	10.08	10.08	10.08	10.08	10.08	10.08
			Parameters			
μ – S tanker	0.19%	n.a.	2.39%	2.39%	2.39%	2.39%
μ – M tanker	4.49%	n.a.	56.13%	56.13%	56.13%	56.13%
μ – L tanker	7.29%	n.a.	91.07%	91.07%	91.07%	91.07%
μ – Cruise ship	7.77%	n.a.	97.17%	97.17%	97.17%	97.17%
μ – Fishing v.	0.31%	0.04%	3.87%	3.87%	3.87%	3.87%
μ – Ro-Ro	0.63%	n.a.	7.87%	7.87%	7.87%	7.87%

Notes: A small tanker category represents a general cargo, a container ship, a heavy load ship and a bulk carrier of small size, i.e. up to 1,000 metric tonnes. Similarly, a medium and a large tanker refer to the same set of vessel types but of size from 1,000 to 1,750 metric tonnes, and above 1,750 metric tonnes, respectively.

APPENDIX D.
A Game-theoretic Analysis

In our model a shipowner has two actions, E and P. We denote their action set by $A_s = \{E, P\}$. Similarly, country's actions are C and N, and country's action set is denoted by $A_c = \{C, N\}$. This holds for both games, although in CIS Pollution game C and N correspond to Comprehensive care and Normal care, while in ABM Pollution game they correspond to Care and Not care, respectively. To follow the following paragraphs, it is enough to remember only that in both games C corresponds to the most environmentally friendly action a country can take.

A strategy of player i, s_i, is a probability distribution that assigns to each action of player i a probability of being selected. In particular, for a shipowner, let p be the probability of choosing E, and 1−p be the probability of choosing P, i.e. $s_s = [E : p \mid P : 1-p]$.

Similarly, for a country, let q be the probability of choosing C, and 1−q be the probability of choosing N, i.e. $s_c = [C : q \mid N : 1 - q]$.

A pair of strategies, (s_s, s_c), where ss and sc correspond to a strategy of shipowner and country, respectively, is called an outcome of the game. A pair of strategies (s_s^*, s_c^*) is a Nash equilibrium if $U_s(s_s^*, s_c^*) \geq U_s(\bar{s}_s, s_c^*)$, for each $\bar{s}_s \in S_s$, and $U_c(s_s^*, s_c^*) \geq U_c(s_s^*, \bar{s}_c)$, for each $\bar{s}_c \in S_c$, where S_s and S_c are the sets of shipowner's and country's strategies, respectively (Nash 1950, 1951). Us (s_s, s_c) and Uc (s_s, s_c) are expected utilities of shipowner and country when shipowner chooses ss and country chooses sc. For $i \in \{s,c\}$, expected utilities are calculated as

$$U_i(s_s, s_c) = pqu_i(E, C) + p(1-q)u_i(E, N) + (1-p)qu_i(P, C) + (1-p)(1-q)u_i(P, N)$$

Table 9.
Mixed Nash equilibrium – General case.

	p*	q*
CIS pollution game	$\frac{(1-\mu)F-C_c}{(1-\mu)F}$	$\frac{C_{mpc}-\mu F}{B+(1-\mu)F}$
ABM pollution game	$\frac{\mu F+C_{mec}^2-C_{mec}-C_c}{\mu F+C_{mec}^2-C_{mec}}$	$\frac{C_{mpc}}{B+\mu F}$

where s_s and s_c are as in paragraph 2 and ui(a_s, a_c) represents player i's utility when shipowner chooses action a_s ϵ As and country chooses action a_c ϵ A_c. Players' utilities for CIS Pollution game and ABM Pollution game are given in respective Tables 1 and 2 in the main text. For example, us(E, C) = B – C_{mpc} and u_c(E, N) = 0.

All our games have a unique Nash equilibrium, as always one of the following two cases occurs. If one of the players has a strictly dominant action, a game has a unique Nash equilibrium in which both players play pure strategies. If none of the players has a strictly dominant action, then the unique mixed Nash equilibrium is given by (s_s*,s_c*) = ([E : p* | P : 1 – p*], [C : q* | N : 1 – q*]), where p* and q* for both pollution games are given in Table 9.

Equilibrium values for p* and q* are obtained by solving the following equations:

$$U_s(E, [C : q \mid N : 1 - q]) = U_s(P, [C : q \mid N : 1 - q]),$$

$$U_c([E : p \mid P : 1 - p], C) = U_c([E : p \mid P : 1 - p], N)$$

which hold in equilibrium and tell that players always choose p and q in a way that makes the other player indifferent between their available actions.