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Abstract European fisheries activities are subject to a hierarchy of regulatory authorities. This raises questions regarding the implications of strategic interaction between different authority levels concerning the regulation of these activities. We apply a bio-economic objective function where fishers and regulators have environmental, economic and social preferences, and where fishers are subject to the aggregate of the regulations set by the various authorities. We analyse one situation where EU authorities set their regulation first, followed by national authorities' regulation, and one situation where the two regulators set their regulations simultaneously. Using data from a survey on preferences among fisheries stakeholders combined with data from the UK nephrops fisheries, this study shows that a hierarchy of regulators with similar preferences will yield higher unit regulations, i.e. higher taxes or higher subsidies than a situation with one regulating authority. When regulators have unequal preferences we may get a situation where one regulator induces a tax on effort, whereas the other offers a subsidy. In this situation the aggregate unit regulation becomes uncertain.

Keywords EU fisheries management · Management hierarchy · Multiple principals · Optimal regulations · Strategic interactions

JEL Classification Q22 · Q28

1 Introduction

Due to the transboundary nature of many fish stocks, fisheries management often requires supra-national institutions to be efficient. Such supra-national institutions are in place for most large-scale transboundary commercial fisheries, either in the shape of regional fisheries management organisations (RMFOs) or via agreements between nations. Examples of the

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latter are the Northeast Arctic cod fisheries, which are managed by a bilateral agreement between Russia and Norway, and the Norwegian Spring Spawning herring fisheries where a multilateral agreement between Iceland, Norway, the Faroe Islands, Russia and the EU is a mainstay of the stock management, prior to more detailed national regulations.

Another example of such a hierarchy of authority levels is the EU fisheries management. The EU Parliament in cooperation with the EU Council set the overarching rules for the fisheries activities, which are formalised in the Common Fisheries Policy (CFP). Given the overarching regulations of the CFP, national authorities are responsible for implementing and enforcing the regulations at a national level. Finally, some countries have POs, that implement the national regulations at a regional level. Regarding division of tasks, the EU authorities each year set the total allowable catch TAC quotas for most commercial species for each (fishing) country. Ideally, this is done based on scientific advice, but also political and social issues may play a role (Gezelius et al. 2008). National authorities distribute the allotted quotas among regional POs or directly to individual fishers. Examples of fisheries managed according to these principles are the Danish and Dutch herring fisheries, where the TAC is distributed directly to individual fishers by national authorities, and some of the UK and French demersal fisheries, where POs allocate their quota share among individual fishers. In all cases the fishing activities are subject to both the EU and the national authorities' regulations, although national authorities have the exclusive right to enforce the TAC and the CFP in general.

The balancing between environmental, economic and social aspects, as required in the EU Marine Strategy Framework Directive, is a challenge fisheries authorities at all levels and in most countries face, and which to date is not resolved. Whereas environmental preferences of fisheries management can be interpreted as harvesting at the maximum sustainable yield (MSY) stock level, economic preferences imply securing that the harvest is carried out efficiently, while social preferences may be concerned with the distribution of quota amongst fishers and the organization of fisheries related economic activities. In this paper, we recognise these inherent challenges in managing fisheries activities in that we analyse (1) how varying preferences regarding the three aspects affect optimal regulations at different levels of the regulatory hierarchy, and (2) how these hierarchical structures affect the optimal regulation within each of the authority levels in the hierarchy. One crucial issue is that preferences regarding the three aspects of fisheries activities may differ between the regulatory levels and that this, in turn, leads to strategic interaction between the respective levels. Applying a model with two principals (authority levels) and one agent (fisheries organization), all with utility functions encompassing environmental, economic and social preferences, we use a Stackelberg and Cournot framework to analyse how the two authority levels set their optimal regulation as best responses to each other, given the preferences of the utility- maximising fisheries organization.

This paper contributes to the economic literature on principal-agent models of fisheries management (see e.g. Jensen and Vestergaard 2002a, b), by introducing two principals with symmetric information, rather than considering one principal and asymmetric information. Further, our paper contributes to the general literature on natural resource management and in particular to the management of the UK nephrops fishery. The results of the paper may be of interest for authorities in all fishing nations with supra-national institutions that manage fishery activities. In Europe, countries outside the EU—and thus not (directly) subject to the CFP—may be interested in the results as they indicate what may happen should they join the EU. This is especially relevant for Iceland and Norway. Countries within the EU and the EU fisheries authorities may be interested in the results as input to the process of understanding why, despite the very comprehensive system of regulations, many of the

European fisheries are in a poor condition COM (2009). Correspondingly, the results of the paper may give insight into the question as to why strong conservationist considerations by the supra-national institutions still may allow overexploitation of the fish stocks.

Theoretical principal-agent models analysing optimal regulations of fisheries activities have been studied by for instance Jensen and Vestergaard (2002a, b, c, 2007). Jensen and Vestergaard (2002a) study an EU-tax on fishing effort as an alternative to the TAC regulation. This paper presents a double principal-agent problem where the national authorities act both as agent, relative to the EU-authorities, and as a principal, relative to the fishers. Another paper using principal-agent theory is Hansen et al. (2006), who derive an optimal tax mechanism to prevent illegal landings and apply this to the Danish cod fisheries in the North Sea. As optimal regulation with a single regulator under symmetric information is a straightforward optimisation problem, all the aforementioned papers introduce asymmetric information between fishers and regulator, and apply contracts which secure information revelation. The aforementioned papers apply an objective function which is simply the economic rent of the harvest, using the short run biological production function. They assume equilibrium harvesting, and both the regulator and the fishers maximise economic rent from the harvest. Whereas Jensen and Vestergaard (2002a, b, c, 2007) maximise economic rent with respect to total effort, Hansen et al. (2006) maximise with respect to individual catches. We extend the objective function applied in the aforementioned papers by including environmental and social in addition to economic preferences for all stakeholders. We use the equilibrium harvesting concept and maximise with respect to total effort. To make the analysis comprehensible and tractable in the empirical case, we assume symmetric information. Whereas Jensen and Vestergaard (2002a) treat the relationship between authorities at different levels as a double principal-agent problem, we solve this issue by applying a sequential and a simultaneous moves model to incorporate the fact that authorities operate at different levels.

Jensen and Vestergaard (2002a, b, c) applied a general formulation of a monetary input regulation (tax), and showed that the equilibrium regulation was fisher specific and non-linear in effort (input). The regulations we use in the analytical model are formulated as so-called Walsh-contracts. Walsh (1995) showed that the optimal contract for a regulating authority, when default is not an option, is linear in the target variable. Campoy and Negrete (2008) extend Walsh's model and show that this is also the case when there are two regulating authorities. Applying Walsh-contracts for regulating authorities at both levels allows analytical solutions of the regulation model. Following Campoy and Negrete (2008), we introduce a participation constraint for the fishers in the regulators' optimisation problem. Applying different types of contracts has consequences for how the equilibrium effort is affected by the regulation. Whereas the general formulation applied by Jensen and Vestergaard (2002a, b, c) implies that a tax results in effort reduction in the form of the most marginal fishers leaving the fishery, the uniform Walsh contract results in all fishers reducing effort by a uniform share. Except for a theoretical paper on optimal fisheries regulations analysed as a common agency (Aanesen and Armstrong 2013) and an applied paper on effects of environmental non-governmental organisations' involvement in fisheries regulations (Aanesen and Armstrong 2014a), optimal regulations with two principals have not been applied to fisheries previously.

Implementation drift defines a situation where rules are fixed at one authority level whereas another authority level, with possibly different preferences, is responsible for enforcing the rules (Blom-Hansen 2005; Gezelius et al. 2008). Implementation drift may cause inefficiencies if preferences are different, as then the enforcing authority may not loyally enforce the rules set by the legislative authority. Instead, it may pursue its own interests by a lax enforcement policy. Gezelius et al. (2008) claim that implementation drift may be used to explain why the relatively strong conservationist preferences present in the CFP, expressed as fishing at the MSY stock level, still results in overexploited fish stocks in most European seas. Whereas we adopt the idea that different authority level's varying preferences may lead to inefficient implementation of the overarching goals, this paper attempts to explain the strategic interaction between the authority levels, eventually leading up to implementation drift.

2 The Model

2.1 Actors, Preferences and Utility

We assume three (groups of) actors; regulating authorities at a superior (international level), regulating authorities at a subordinate (national) level, and fisheries' representatives, e.g. a producer organization, which is subordinate to both authorities' regulations. All three actors have preferences with respect to the outcome of the fishing activity in a specific single species fishery, and these preferences can be divided into three categories; environmental, economic and social. We assume that these preferences can be expressed by a utility function, which is a weighted sum of the three preferences. The utility function of each of the three actors can thus be formulated as in (1).

$$U^k = \beta_1^k ENV + \beta_2^k ECN + \beta_3^k SOC, \quad k \in \{EU, N, F\} \tag{1}$$

U^k is the utility level, and the superscript k indicates the actor under consideration; $k = EU$ denotes EU authorities, $k = N$ denotes national authorities, and $k = F$ denotes a fisheries organization. β_j^k, $j = 1, 2, 3$, is the weight of preference j to actor k, where $j = 1$ indicates the environmental preference, $j = 2$ indicates the economic and $j = 3$ indicates the social preference. We assume $\sum_{j=1}^{3} \beta_j^k = 1$ for all k.

ENV, ECN and SOC are functions, representing the three preference categories. The Green paper on the 2012 reform of the CFP, states that one of the most prominent future targets for the CFP is to fish within the MSY (COM 2009). Hence, it is realistic to assume that the environmental preference establishes that utility increases with fish stock size up to the MSY-level, X_{MSY}. As a proxy for the environmental preference we thus use the long run equilibrium harvest function, $ENV = h(E, X)$, assuming equilibrium harvesting, i.e. $\dot{X} = F(X) - h(X, E) \equiv 0$, where E is effort and X is stock size. Applying a logistic growth function of the form $F(X) = rX\left(1 - \frac{X}{K}\right)$, the long run harvest function is given by $h(E, X) = qKE\left(1 - \frac{qE}{r}\right)$, where r is the intrinsic growth rate, q is a catchability parameter, expressing the accessibility to the fish stock, and K is the carrying capacity of the stock. In order to express the harvest in monetary terms we multiply by a constant P, representing the societal unit value of the stock. This formulation of the environmental preference implies that beyond the MSY level utility decreases when the stock level increases.[1]

The economic preference is represented by the steady state sustainable economic rent in the fishery, given by $ECN = \Pi(E, X) \equiv ph(X, E) - aE$, where p is the price per unit catch and a is the unit price of effort, all expressed in monetary terms. The maximum economic

[1] Clearly, in an uncertain world better protection could be obtained at higher stock levels than MSY. Whereas this technically can be implemented in our model, it makes the model analytically less tractable without adding much to the results. It would increase the optimal unit regulation (when a tax) somewhat and thus reduce the optimal effort compared to the model we use in this paper. In another paper, Aanesen and Armstrong (2014a), we apply an objective function where utility does not decrease in the stock size beyond the MSY stock level.

rent, which is possible to sustain over time, is given by the maximum economic yield (MEY) stock level, X_{MEY}, and effort E_{MEY}. Note that p and P, representing respectively the unit market price of the species harvested in the fishery under consideration and the opportunity cost of the stock as regarded by the society, may coincide, but this is not a precondition.

The social preference is represented by the employment in the fishery, and we assume this is positively correlated with the use of effort in the fishery. Hence, we set $SOC = f(E) \equiv SE$, where S is a constant at the same time transferring effort into employment and assigning a societal value to employment in the fishery, i.e. expressing it in monetary terms. Hence, inserting for the long run equilibrium harvest function and the function for the social interest, the utility function for actor k, $k \in \{EU, N, F\}$, given in (1) can be specified as follows:

$$U^k = \beta_1^k PqKE\left(1 - \frac{qE}{r}\right) + \beta_2^k \left(pqKE\left(1 - \frac{qE}{r}\right) - aE\right) + \beta_3^k SE, \quad k \in \{EU, N, F\} \tag{1'}$$

whereas the assumption that regulating authorities at all levels hold environmental, economic as well as social preferences regarding fisheries activities is acceptable, making the same assumption about a fisheries organization may require some explanation. Note that (1′), when $k = F$, is the utility as expressed by a fisheries producer organization, henceforth denoted fisheries organization. The size of such an organization, measured in the number of active fishers, will be positively related to the organization's power to influence management decisions. The higher the TAC in a specific fishery, the higher may the effort in the fishery be, and the higher the number of fishers the fishery can sustain. Thus, it should be acceptable to assume that the number of active fishers contributes positively to the organization's utility. Perhaps in contrast to individual fishers, a fisheries organization may derive utility from a stable, long run production level as this will maintain the outcome for its members, and thus ensure their membership in the long run. This interest is taken care of by the long run production function, which expresses a preference for fishing at the MSY-level. On the other hand, the organization also has an interest in a highest possible (long run) outcome for its members, expressed by the long run profit function, which defines a preference for fishing at the MEY-level. In order to be able to solve the model analytically we assume fishers are homogenous members of the fisheries organization.

2.2 The Regulation Model

For model tractability reasons we restrict the authorities' use of regulations to one specific regulation; a tax on effort (input tax). Although not frequently used in fisheries regulations, this input regulation can readily be transformed into an output regulation, such as a tax on landings, which in turn corresponds to a resource tax. This is done by assuming a fixed relationship between effort and output. Further, when the national TACs are distributed among individual fishers by the use of transferable quotas, which if acquired anew each year, the quota price can be interpreted as a resource tax.

The reason why we choose to focus on an input regulation is that it allows a more advanced analysis of the interaction between fishers' harvest behavior, harvesting costs and the regulations. Also, it makes the results from our analysis comparable to results from previous analyses of optimal regulations. Admittedly, effort is a heterogeneous concept, which contains various input factors. However, as is commonly assumed in bio-economic models, we assume that the optimal, i.e. cost-minimizing, combination of input factors is derived and this combination is denoted effort. In this paper we assume that the input regulation is expressed per unit effort.

According to Campoy and Negrete (2008, 2010), in the two regulator case the regulators have to impose a participation constraint when deriving the optimal regulation by maximizing the utility. Translated into a fishery context this means that it must be in the fishers organization's interest to remain in the fishery also after the regulation is introduced. Hence, in addition to the unit input regulation, the optimal contract must also contain a lump sum transfer. This transfer can be either positive or negative, denoting either a transfer from the fisheries organization to the regulators or the other way around. As an example, if the tax is set so high that the organization's utility of staying in the fishery becomes negative, it must be compensated. Correspondingly, if the regulators' optimal effort and thus harvest is higher than the level implemented by the fisheries organization they may increase effort by offering a subsidy. In this case, if the subsidy implies economic rent, the lump sum transfer can be formulated as a fee to participate in the fishery (from the fisheries organization to the regulators).

The formulation of the regulation when there is only one regulator is given by

$$W = w_0 + w_1 E \tag{2}$$

where w_1 is a unit input regulation on effort, w_0 is a lump sum transfer, and W is the regulation revenue from the fisher' organization to the regulator.

The formulation of the regulation allows the following interpretation of the equilibrium results: If EU authorities set a strict regulation i.e. a high tax (which can be interpreted as a "low" TAC), and national authorities set a lax regulation (which can be interpreted as a lax enforcement of the TAC), or even a negative regulation (subsidy, which can be interpreted as allowing overfishing), this can be interpreted as if national authorities act disloyally and perform a lax enforcement of the EU regulation, or even set their own regulation which counters the EU regulation. Similarly, a strict regulation (high tax/"low" TAC) at the EU level accompanied by a strict regulation at the national level can be interpreted as though national authorities strictly and loyally enforce the EU regulation and ensure that the TAC is implemented.

The main reason for regulating fisheries activities is the intertemporal stock externality, i.e. the fact that whereas benefits of fishing beyond the economically optimal harvest level (MEY) are private, the costs, including higher future harvesting costs due to a lower stock, are public. When the fishers have solely economic preferences, i.e. maximizing the individual rent of the harvest activity, they will, due to the stock externality, end up in the open access solution where the effort is higher and the stock level lower compared to what is socially optimal. The lump sum transfer part of the regulation we apply will ensure that, in equilibrium, the economically optimal level of effort is applied, and the rents are extracted by the authorities. Hence, the stock externality is internalised, and we avoid the open access solution, despite the fishery still being de facto open access. This is equivalent to the standard bioeconomic model when maximising economic rent and applying effort taxes.

3 Optimal Unit Input Regulation with One and Two Regulators

We assume that all actors maximize utility given in ($1'$), and solve the model as a static two step constrained maximization problem. First, the regulator(s) determine the optimal unit input regulation and lump sum transfer. Next, the fisheries organization decides the optimal effort, and thus harvest, given the regulation(s). The equilibrium solution is characterized by the fact that the effort chosen by the organization is a best reply to the regulations set by the regulators. On the other hand, the regulations the fisheries organization face is fixed such that it induces the organization to choose the effort level, which the regulators prefer. Since we have assumed that the organization consists of homogenous fishers, once the number of fishers is decided the effort is automatically given, and the vice versa. The regulations set by each of the regulators are best replies.

3.1 Optimal Unit Input Regulation with Only National Authorities

The benchmark model, assuming that only national authorities regulate the fishery, is a straightforward constrained optimisation problem, given by

$$\max U^N = \beta_1^N PqKE\left(1-\frac{qE}{r}\right)+\beta_2^N\left(pqKE\left(1-\frac{qE}{r}\right)-aE\right) + \beta_3^N SE+\eta\left(w_0+w_1E\right) \tag{3}$$

$$\text{s.t.}\quad \beta_1^F PqKE\left(1-\frac{qE}{r}\right)+\beta_2^F\left(pqKE\left(1-\frac{qE}{r}\right)-aE\right) + \beta_3^F SE-\left(w_0+w_1E\right)\geq 0 \tag{4}$$

$$\dot{X}\equiv F(X)-h(E,X)=0 \tag{5}$$

where (3) is the objective function of the national authorities given the use of a regulation formulated as a Walsh-contract. The parameter $\eta, 0\leq\eta\leq 1$, gives the share of the regulation revenue which accrues to the regulator, and for simplicity and without consequences for the analytical solution we assume $\eta=1$. Equation (4) is the participation constraint, demanding that the fishers organization's net utility is non-negative. Equation (5) secures that the stock is in steady state, i.e. that the harvest does not exceed the natural (net) growth, and we can focus on a static, one-shot solution. The solution to (3)–(5), yields the optimal effort level for the national authorities:

$$E_N^*=\frac{r\left[qK\left(\Gamma^N+\lambda\Gamma^F\right)-Q^N-\lambda Q^F+(1-\lambda)\,w_1\right]}{2q^2K\left(\Gamma^N+\lambda\Gamma^F\right)} \tag{6}$$

where $\Gamma^i=P\beta_1^i+p\beta_2^i$, $Q^i=a\beta_2^i-S\beta_3^i$, $i\in\{N,F\}$, and λ is the Lagrange multiplier, denoting the shadow price of fisheries activities.

The optimal total effort for the fisheries organization is found by maximising the left hand side of (4) with respect to E, yielding

$$E_F^*=\frac{r\left[qK\Gamma^F-\mathrm{Q}^F-w_1\right]}{2q^2\mathrm{K}\Gamma^F} \tag{7}$$

Equalising (6) and (7) and solving for w_1 yields the optimal unit regulation

$$w_1^*=\frac{\left(Q^N\Gamma^F-Q^F\Gamma^N\right)}{\Gamma^N+\Gamma^F} \tag{8}$$

The regulation in (8) implements the authorities' preferred effort level as given in (6). Equation (8) shows that the optimal unit regulation, w_1^*, unambiguously decreases in β_3^N, i.e. the social preferences of the authorities. This is reasonable as the more weight put on the social preference in the utility function, and correspondingly lower weight on the economic and environmental preferences, the higher will the optimal effort be. On the other hand, the equilibrium unit regulation unambiguously increases in β_3^F, i.e. in the weight of the social preferences of the fishers organization. For the other preference weights the results are ambiguous. The larger the variation in preferences between regulator and fisheries organization are, the more significant is the unit regulation. Note that when the authorities and the fisheries organization weight the preferences equally, the optimal unit regulation equals zero. However, the regulator still will use the lump sum transfer to confiscate eventual rent in the fishery. The lump sum transfer, accompanying the unit regulation in (8) is found by solving (4) with respect to w_0, yielding

$$w_0^* = h(E, X)\Gamma^F + EQ^F - w_1^* E \tag{9}$$

Remembering that w_0 is formulated as a lump sum transfer from the fisheries organization to the authorities, (9) shows that w_1^* and w_0^* are inversely related, meaning that the higher the tax rate is, the more likely it is that the authorities must offer a transfer to the fisheries organization, i.e. $w_0^* < 0$. The equilibrium regulation, (w_0^*, w_1^*), implies that the regulator confiscates all rent, and hence there is no incentive for the fisheries organization to let in new fishers.

3.2 Optimal Unit Input Regulation with Two Regulators

We now assume an EU-fishery regulated both at EU and national level. Both regulators apply a Walsh contract in the regulation of the fishery, and the fisheries organization will face a regulation, which is the aggregate of EU and national authorities' regulations. We assume two types of strategic interaction between EU and national authorities; (1) the two regulators set their regulation sequentially, starting with the EU authorities, (2) the two regulators set their regulation simultaneously. Situation (1) describes the regulatory hierarchy as it is intended to work, i.e. the EU authorities first set the overarching regulations, and then the national authorities follow up by enforcing the overarching regulations and setting supporting regulations. A few papers, e.g. Gezelius et al. (2008) claims that one reason for overfishing in many EU-fisheries is implementation drift. If this is the case, national authorities may set their regulation (or decide their enforcement) on their own premises and pursuing their own interests (preferences) rather than supporting the EU regulations. This calls for model 2) with two "equal" regulators.

Situation 1: EU and national authorities set their regulations sequentially

When the strategic interaction between the two authority levels is sequential, i.e. that EU authorities first fix their optimal regulation and then national authorities set their regulation, the optimisation problem of EU authorities is given by

$$max U^{EU} = \beta_1^{EU} PqKE\left(1 - \frac{qE}{r}\right) + \beta_2^{EU}\left(pqKE\left(1 - \frac{qE}{r}\right) - aE\right)$$
$$+\beta_3^{EU} SE + \rho\left(v_0^S + v_1^S E\right) \tag{10}$$
$$\text{s.t.}\quad \beta_1^F PqKE\left(1 - \frac{qE}{r}\right) + \beta_2^F\left(pqKE\left(1 - \frac{qE}{r}\right) - aE\right)$$
$$+\beta_3^F SE - \left(t_0^S + t_1^S E\right) - \left(v_0^S + v_1^S E\right) \geq 0 \tag{11}$$
$$\dot{X} \equiv [F(X) - h(E, X)] = 0 \tag{12}$$

where $0 \leq \rho \leq 1$ is the share of the regulation revenue to EU authorities, and v_0^S, v_1^S, are the lump sum transfer and unit input regulation respectively set by EU authorities. For simplicity and without consequences for the model result we assume $\rho = 1$. National authorities' maximisation problem is given by (3)–(5) when in (3) $(w_0 + w_1 E)$ is replaced by $\left(t_0^S + t_1^S E\right)$ and in (4) $(w_0 + w_1 E)$ is replaced by $\left(\left(t_0^S + t_1^S E\right) + \left(v_0^S + v_1^S E\right)\right)$. Note that we let the share of the regulation amount accruing to national authorities, given by η, remain the same in the two situations. The main difference from the authorities' optimisation problem in the benchmark model is that the fishers organization's participation constraint, given by (11), now takes into account two regulations instead of one. Hence, the way each regulator takes into account the presence of another regulator is through the effect the other regulation has on the fishers organization's behaviour. Maximising the objective functions of the two regulators with respect to E yields the optimal effort levels, as seen from the perspective of the regulators.[2] Equalising the optimal effort level for the fisheries organization and for each of the regulators yields the reaction functions for each regulator, given by (13) and (14).

$$v_1^{SR} = -\frac{\left(\Gamma^N + \Gamma^F\right)\left(\Gamma^{EU} + \lambda\Gamma^F\right)}{\Gamma^{EU}\left(\Gamma^N + \Gamma^F\right) + \Gamma^F\left((1+\lambda)\Gamma^N + \Gamma^F\right)} t_1^S + \frac{\left(Q^{EU}\Gamma^F - Q^F\Gamma^{EU} + \lambda\Gamma^F w_1^*\right)\left(\Gamma^N + \Gamma^F\right)}{\Gamma^{EU}\left(\Gamma^N + \lambda\Gamma^F\right) + \Gamma^F\left((1+\lambda)\Gamma^N + \Gamma^F\right)} \tag{13}$$

$$t_1^{SR} = -\frac{\Gamma^N}{\Gamma^N + \Gamma^F} v_1^S + \frac{\left(Q^N\Gamma^F - Q^F\Gamma^N\right)}{\Gamma^N + \Gamma^F} \tag{14}$$

Equation (14) shows that the last right hand term coincides with the optimal unit regulation when national authorities are the sole regulator. Hence, the first right hand term represents the "strategic" effect, i.e. how national authorities react to the regulation set by EU authorities. This effect shows that when the optimal unit regulation for both regulators is a tax or a subsidy, national authorities will reduce their unit regulation compared to if they were the sole regulator. If, however, EU authorities set a unit tax, whereas national authorities would offer a subsidy were they the sole regulator, such that both the first and the last term of the right hand side of (14) is negative, then national authorities will increase their subsidy as a response to the introduction of an EU-tax in the fisheries management. This in order to offset the effects of the EU-tax imposed on the national fishery, represented by the fisheries organization. Similarly, the first right hand term of Eq. (13) shows a direct strategic effect of national authorities' regulation on the EU regulation. This has the same characteristics as the EU-regulation on the optimal national authorities' regulation described above. On the other hand, the last right hand term does not express merely the regulation as it would have been were the EU the sole regulator, as this would in that case equal $\frac{\left(Q^{EU}\Gamma^F - Q^F\Gamma^{EU}\right)}{\Gamma^{EU} + \Gamma^F}$). It can, however, be shown that when national and EU authorities have high environmental and low social preferences and the vice versa for the fisheries organization, then the last right hand term of (13) is larger than the regulation the EU would have set were they the sole regulator. This contributes to increase the unit regulation set by EU authorities. Under the same conditions, however, the first right hand side term of (13) will contribute to reduce the EU regulation and we need numerical examples, as those in Sect. 4, to identify which yields the larger contribution.

Solving for the reaction functions yields the explicit optimal regulations for each regulator, and these are given in the "Appendix 6.1". The aggregate regulation, which the fisheries organization faces, is

$$v_1^{S*} + t_1^{S*} = \frac{\left(Q^{EU}\Gamma^F - Q^F\Gamma^{EU}\right) + \left(\Gamma^N + \Gamma^F\right) w_1^*}{\Gamma^{EU} + \Gamma^N + \Gamma^F} \tag{15}$$

[2] The expressions for optimal effort for each of the actors are given in the "Appendix 6.1".

The effort implemented by the fisheries organization given the aggregate regulation in (15) is

$$E_F^{S*} = \frac{r\left[qK\Gamma^F - Q^F - (v_1^{S*} + t_1^{S*})\right]}{2q^2 \mathrm{K}\Gamma^F} \tag{16}$$

The optimal regulation with only one authority level implies that the fishers organization's participation constraint is fulfilled with equality. This must also be the case with two authority levels when formulating their mutually optimal regulations, as otherwise one authority may change her regulation, and thus utility, and the aggregate of the two regulations will still be accepted. Hence, in equilibrium $U^F\left(v_0^S, v_1^S, t_0^S, t_1^S\right) - v_0^S - t_0^S = 0$, where v_0^S is the regulation revenue (confiscated rent) to the EU authorities and t_0^S the regulation revenue to the national authorities. In order not to be tempted to accept only one of the regulations, the following must be fulfilled; $U^F\left(v_0^S, v_1^S, 0, 0\right) - v_0^S - t_0^S = U^F\left(0, 0, t_0^S, t_1^S\right) - v_0^S - t_0^S < U^F\left(t_0^S, t_1^S, v_0^S, v_1^S\right) - v_0^S - t_0^S$. For these conditions to hold, the lump sum transfers, t_0^{S*} and v_0^{S*} no longer individually need to satisfy the participation constraint of the fisheries organization, but the aggregate must ensure that the organization's participation constraint, given in (11) is fulfilled.

Situation 2: EU and national authorities set their regulations simultaneously

When both authorities set their regulation simultaneously, EU authorities' maximisation problem is given by (10)–(12) when in (10) $(v_0^S + v_1^S E)$ is substituted by $(v_0^C + v_1^C E)$, and in (11) $\left(t_0^S + t_1^S E\right) - \left(v_0^S + v_1^S E\right)$ is substituted by $\left(t_0^C + t_1^C E\right) - \left(v_0^C + v_1^C E\right)$. v_0^C, v_1^C are the lump sum transfer and unit input regulation respectively set by EU authorities, whereas $\left(t_0^C, t_1^C\right)$ are the corresponding variables in national authorities' regulation when regulations are set simultaneously. National authorities' maximisation problem is given by (3)–(5) when in (3) $(w_0 + w_1 E)$ is replaced by $\left(t_0^C + t_1^C E\right)$, and in (4) $(w_0 + w_1 E)$ is replaced by $\left(\left(t_0^C + t_1^C E\right) + \left(v_0^C + v_1^C E\right)\right)$. This is also shown in "Appendix 6.2".

As in situation (1) each optimal unit regulation is a function of the regulation set by the other regulator, and the reaction functions of each regulator when they set their regulation simultaneously are given in (17) and (18).

$$v_1^{CR} = -\frac{\Gamma^{EU}}{\Gamma^{EU} + \Gamma^F} t_1^C + \frac{\left(Q^{EU}\Gamma^F - Q^F\Gamma^{EU}\right)}{\Gamma^{EU} + \Gamma^F} \tag{17}$$

$$t_1^{CR} = -\frac{\Gamma^N}{\Gamma^N + \Gamma^F} v_1^C + \frac{\left(Q^N\Gamma^F - Q^F\Gamma^N\right)}{\Gamma^N + \Gamma^F} \tag{18}$$

Equation (18) coincides with (14) and thus national authorities' behaviour is as in situation (1). As the two regulators are now symmetric, EU authorities' behaviour can also be interpreted as for national authorities in situation (1).

With two regulators the fisheries organization faces the aggregate of the two unit input regulations, which is given by[3]

$$v_1^{C*} + t_1^{C*} = \frac{Q^{EU}\Gamma^F - Q^F\Gamma^{EU} + Q^N\Gamma^F - Q^F\Gamma^N}{\Gamma^{EU} + \Gamma^N + \Gamma^F} \tag{19}$$

The optimal effort level when there are two regulators is given by

$$E_F^{C*} = \frac{r\left[qK\Gamma^F - Q^F - \left(v_1^{C*} + t_1^{C*}\right)\right]}{2q^2 \mathrm{K}\Gamma^F} \tag{20}$$

[3] The explicit expressions for the optimal regulations with two regulators setting their regulation simultaneously are given in the "Appendix 6.2".

Note that in the case of two regulators with contrasting interests, one of which will aim at setting a tax and the other a subsidy, the final regulation may be close to zero, as can be seen from (19). In contrast to when there was only one regulator, coinciding interests between one regulator and the fisheries organization no longer implies that the regulation equals zero. The reason is that there still is an interaction between the two regulators, given by the first right hand term in (17) and (18). Only when all actors have coinciding interests will the optimal regulation equal zero. In this situation, however, the lump sum transfers to the two regulators will be positive as long as there is rent in the fishery.

Comparing (15) and (19), it can be shown that the aggregate regulation in the two cases coincides. This means that the strategic interaction between the two regulators does not affect the aggregate regulation, only its distribution between the two regulators. We will come back to this in our numerical example in Sect. 4.

The unit regulation when regulated at two authority levels (EU and national) is higher compared to with only one regulating authority when

$$\Gamma^F\left(Q^{EU}\left(\Gamma^N+\Gamma^F\right)-\Gamma^{EU}\left(Q^N+Q^F\right)\right)>0 \tag{21}$$

when EU authorities have lower social preferences than both the fisheries organization and national authorities, whereas the fisheries organization and national authorities have more equal social and economic preferences, making Q^F and Q^N very low, the probability that (22) is fulfilled is high. Taking into consideration that the social preferences refer to the number of persons employed in the fisheries (effort), it is possible to argue that this probably is of more concern for local (and national) authorities and fisheries organization than it is for EU authorities. On the other hand, even if EU authorities have high social preferences, our model does not necessarily give higher unit regulations in a hierarchy of regulators compared to the situation with one single regulator.

4 Empirical Data and Application of the Model

4.1 The UK Nephrops Fishery in the North Sea and East Irish Sea

The UK nephrops fishery takes place off the coast of Scotland in the North Sea and the East Irish Sea. There are also UK vessels harvesting nephrops in the West Irish Sea and in the Celtic sea. These areas are shared with Irish and French vessels. In this presentation we concentrate on the UK nephrops fisheries in the two former areas. This is a fresh consumption fishery, and often combined with fishing for other demersal species like cod and haddock (Bailey et al. 2012). However, in 2008, 86 % of the catch value originated from nephrops for the single-rig trawlers, whereas the corresponding share was 77 % for double-rig trawlers. Table 1 shows the development in abundance (number of individuals transferred into tonnes), catches and catch per unit effort (CPUE) for the years 1995–2008.

Whereas abundance rose and catches declined from 1995 to 2005, in 2006 there was an abrupt change with a strong increase in catches, and a fall in abundance in 2007. CPUE has increased steadily during the whole period. Effort is measured in number of fishing hours, and effort declined from 320.000 h in 1995 to 220.000 h in 2005. In 2008 the total number of fishing hours was about 282.000 for the UK fleet. The steady decrease in effort hours whereas catches have increased the last years (from 2006 on), explains the increase in CPUE. One major explanation for this is the fact that twin-rig trawlers doubled from 2005 to 2007, and that they are far more efficient than single-rig trawlers (Curtiz et al. 2010).

Table 1 SSB and catches in tonnes, CPUE in catches in tonnes per effort hour

Year	Abundance	Catches	CPUE
1995	89,563	12,714	0.039
1996	134,642	11,315	0.034
1997	112,347	11,398	0.034
1998	157,356	11,403	0.034
1999	110,877	11,685	0.036
2000	161,171	11,184	0.036
2001	176,291	10,965	0.038
2002	182,346	10,705	0.042
2003	201,735	10,694	0.043
2004	222,035	10,500	0.0455
2005	222,315	10,820	0.049
2006	227,600	14,120	0.058
2007	146,437	17,034	0.066
2008	189,941	16,024	0.0665
2009			n.a.

Source: ICES, database and advice (2008)

Table 2 Bio-economic model parameters

Intrinsic growth rate, r	0.144
Catchability, q	0.0000002778
Carrying capacity, K, tonnes	349,808
Unit price, p, Euro per tonnes	2,500
Unit harvest cost, a, Euro per unit effort	57.25

Sources: COM (2008), ICES (2008), own estimations

The UK nephrops fishery is regulated by a TAC, set by the EU, which in turn is distributed among individual vessels by national authorities. In addition, there are by-catch regulations in the form of minimum mesh size, in order to avoid the catch of undersized demersal fish. Further input regulations are restrictions on days at sea and the use of selection grids. The fishery enjoys a fuel tax exemption (subsidy).

Table 2 shows empirical and estimated biological and economic data of the UK nephrops fishery.

Whereas q, r and K are estimated based on time series data on effort and catches, assuming equilibrium harvest, p is taken from the Annual economic report for EU fisheries (COM 2008), and a is taken from the annual economic report on UK fisheries (Curtiz et al. 2010). The opportunity cost of the fish stock, P, and of fishery employment, S, are for simplicity set equal to their market counterparts, i.e. $P = p$, $S = a$.

4.2 Preferences

As was shown in Sect. 2 the equilibrium expressions for effort and regulation crucially depend on the weight of the stakeholders' preferences. A survey on preferences connected to fisheries activities was made among Danish, Dutch, French, Irish, Norwegian, Portuguese, Spanish and UK representatives for various fisheries stakeholder groups (Aanesen et al. 2014b).[4] The

[4] This was done in the EU-funded FP7 project "Making the European Fisheries Ecosystem Plan Operationable".

Table 3 Preference weights for the actors

Type of preference	Fisheries representatives	National authorities	EU authorities
Environmental	0.36	0.50	0.48
Economic	0.36	0.28	0.29
Social	0.28	0.22	0.23

Source: Aanesen et al. (2014b)

survey was carried out as a deliberative process, where stakeholders representing fisheries, including both individual fishers and POs, national and EU authorities, and NGOs from the mentioned countries were invited to take part in a one day workshop. During the workshop the participants listened to presentations of the three pillars of sustainable fisheries management; environmental, economic and social.[5] Subsequently, they were asked to give input on which, according to their opinion, were the most crucial aspects to take into consideration if European fisheries management should be more sustainable. As part of their input, they were asked to fill in a form where they should distribute a total of 100 points on the three pillars of sustainable fisheries management. Table 3 shows aggregated average number of points, expressed as weights, assigned by national fisheries authorities, EU fisheries authorities, and fisheries representatives, henceforth called fisheries organization.

Table 3 shows that the weighting of the three pillars of fisheries management are very similar among EU and national authorities' representatives. The fisheries organization has the most equal distribution of weights among the three pillars, and as expected the highest social preferences, but also the highest economic preferences.

4.3 Optimal Input Regulation of the UK Nephrops Fishery

Using the optimal regulation models, as derived in Sect. 3, and the numerical values of the bio-economic parameters and preferences weights in Tables 2 and 3, the optimal effort for the national authorities, when the sole regulator, is 253.200 effort hours. This is higher than the optimal effort for the fisheries organization, who prefer "only" 252.100 effort hours given the preferences in Table 3. Whereas the high social preferences imply a high effort, the fact that the fisheries organization also has higher economic preferences, for which the MEY describes the preferred effort level, contributes to explain the lower optimal effort level for the fisheries organization. In order to motivate the organization to increase effort (slightly), the authorities offer a subsidy equal to £ 0.73 per effort hour. This is shown in Table 4a. If we assume that the actual mean effort in the fishery for the period 1995–2008, which is 281,500 effort hours, is the preferred effort level for the fisheries organization,[6] then the authorities will impose a tax on £ 20 per effort hour in order to reduce the effort to their preferred level of 253.200 effort hours (shown in Table 4b).

When we take into consideration that the nephrops fishery is subject to both EU and national authorities' regulations, and that the EU authorities set their regulation first, the EU authorities will offer a subsidy equalling £ 0.45 per effort hour. As a response, the national authorities offer a subsidy equalling £ 0.5 per effort hour, which is lower compared to when they were the sole regulator. In total this yields an aggregate regulation of £ 0.95 per effort

5 The three pillars were expanded upon with regards to descriptors and indicators, but this is not necessary for the current analysis.

6 This is the case with the following preference structure for the fishers; $\beta_1^F = 0.3$, $\beta_2^F = 0.1$, $\beta_3^F = 0.6$.

Table 4 Optimal regulation, (a) measured in £, (b) optimal regulation in £, with adjusted preference weights for the fishers' organization, with one and two regulators, sequential and simultaneous moves

	National authorities	EU authorities	Aggregate unit regulation	Optimal effort level
(a)				
Sequential moves				
One regulator	−0.73	–	−0.73	253,200
Two regulator	−0.5	−0.45	−0.95	253,550
Simultaneous moves				
One regulator	−0.73	–	−0.73	253,200
Two regulator	−0.48	−0.47	−0.95	253,550
(b)				
Sequential moves				
One regulator	20	–	20	253,200
Two regulators	12.02	12.14	24.16	270,750
Simultaneous moves				
One regulator	20	–	20	253,200
Two regulators	11.99	12.17	24.16	270,750

hour. When the regulations are set simultaneously, the optimal regulation for EU authorities is a subsidy equalling £ 0.47 per effort hour, whereas the national authorities set a subsidy equal to £ 0.48 per effort hour. In total this yields a subsidy equalling £ 0.95 per effort hour, which is the same as in the sequential game only that the composition of the regulations now has changed. The implemented effort equal 253.550 effort hours, which is a "compromise" between the optimal effort of the two regulators. In the sequential game the EU share of the regulation is lower and the share of the national authorities higher compared to in the simultaneous game. Compared to the situation with only one regulator, two regulators yields a less strict regulation in the form of a subsidy.

The preference weights given in Table 3 imply that both authority levels want a higher effort than the fisheries organization. One reason for this is the relatively high economic preferences of the fisheries organization, which means fishing at the MEY level. Hence, the authorities subsidize effort.

In order to relate our model to the actual nephrops fishery activities during the period 1995–2008, we use as benchmarks the average number of implemented effort hours as the preferred effort level first for fisheries representatives and in a second example for authorities. Then we use the model to derive the optimal regulations, given in Table 4b. The mean annual fishing hours for the period 1995–2008 is 282.000 effort hours. If we, as above, use this as the preferred and actual effort level of the fisheries organization, which implies reducing their economic and increasing their social preferences[7] while keeping the preferences of the regulators unchanged, the optimal regulation when the EU authorities set the regulation first, is a tax equalling £ 12.14, and as a response the national authorities set a tax equalling £ 12.02. Hence, the total regulation is a tax equal to £ 24.16 per effort hour. When setting their regulations simultaneously the optimal regulations are a tax equal to £ 12.17 and £ 11.99 per effort hour respectively for the EU and the national authorities. Again, the EU share of

[7] With two regulators, one set of fishers' preferences which give this preferred effort level is $\beta_1^F = 0.36$, $\beta_2^F = 0.21$, $\beta_3^F = 0.43$.

Table 5 Sensitivity analysis

	p	a	P	S	r	K	q
Effort	0.1	−1.0	0.12	0.75	10	0.2	−8.9
Unit regulation	−3.3	39.5	3.25	−29.25	0	0	0

% Change in equilibrium effort and regulation for a partial 10 % increase in the background variables

the regulation is lower and the national authorities' share is higher in the sequential game compared to in the simultaneous game. The total regulation of £ 24.16 yields 270,750 effort hours. This is shown in Table 4b.

Finally, we assume that the actual annual TAC represents the preferences of the EU authorities, as they are responsible for setting the TAC. The mean annual TAC over the years 1995–2008 is 13,650 tonnes. With a mean CPUE for the same period equal to 0.04435 this implies a mean annual number of effort hours equal to 307,800.[8] Manipulating the preferences of the EU authorities so that 307,800 is their preferred effort level,[9] while the preferences of the national authorities and the fisheries representatives are given as in Table 3, the EU authorities, when acting first, will offer a subsidy equalling £ 31 per effort hour. The national authorities will counter and impose a tax upon effort equal to £ 15.4 per effort hour. In sum the regulations equal a subsidy on effort equal to £ 15.6 per effort hour. Had the national authorities set their regulation simultaneously with the EU authorities, the EU regulation would be a subsidy equal to £ 16.6 and the national authorities would forward a tax equal to £ 1.00 per effort hour. The total regulation results in the implementation of 275,150 effort hours. Note that now the regulations of the two authority levels differ significantly, whereas the two regulations were quite similar in the previous examples. The reason, obviously, is the changes made in the EU authorities preferences. Whereas the EU and national authorities originally had almost coinciding preferences (see Table 3), and thus set almost identical optimal regulations, changing the EU authorities' preferences implies that the optimal EU regulation will now differ markedly from that of the national authorities.

The model results for optimal unit regulation and optimal effort presented above are (largely) robust to changes in the model parameters, and Table 5 gives %-change in effort and unit regulation for a 10 % change (increase) in the background variables for the two regulators simultaneous move model, using the preferences given in Table 3.

Changes in the biological parameters, r, K and q, do not affect the optimal unit regulation, but they have effects on optimal effort, and thus harvest. A change in the economic parameters changes both the optimal effort level and unit regulation. Especially a change in the unit effort cost, a, and in the social value of fisheries employment, S, have over-proportional effects on the unit regulation. Whereas a 10 % increase in unit costs increases the unit regulation (when expressed as a subsidy) by 39 %, the same change in the social value of fisheries employment reduces the subsidy with almost 30 %.

5 Discussion and Conclusions

This paper analyses strategic fisheries regulations under varying preferences (environmental, economic and social) for fishers and regulators and in the presence of one (national authority)

[8] Note that this exceeds the MSY level and thus does not represent a steady state solution.

[9] This is the case with the following preference structure for the EU authorities; $\beta_1^{EU} = 0.29$, $\beta_2^{EU} = 0.04$, $\beta_3^{EU} = 0.67$.

and two (EU and national authorities) regulators. The regulation applied is formulated as a Walsh contract, which on the one hand regulates effort by either taxing or subsidising it (unit regulation), and on the other hand either confiscates rent or compensates for economic losses (lump sum regulation). We discuss the strategic interaction between the two regulators and show that their optimal unit regulation depends on a combination of the regulators' preferences and the strategic interaction between them.

Varying preferences contribute significantly to explaining differences in unit regulation. In a survey among fisheries stakeholders (Aanesen et al. 2014b), EU and national fisheries authorities are shown to have rather similar preferences regarding fisheries activities. Applying these preferences in our regulation model yields relatively equal optimal unit regulations for the two regulators, as either both choose a tax or both offer a subsidy to the fishers independent of their strategic interaction. With similar preferences the regulators regard their respective regulation as strategic substitutes (Bulow et al. 1985). When two regulations are regarded as strategic substitutes the optimal response for e.g. the national authorities to more aggressive play by the EU authorities is to play less aggressively (op cit). Then EU authorities can utilise a first mover advantage and act more aggressively knowing that national authorities will respond by playing less aggressively. This is demonstrated by the results in Table 4a, b in Sect. 4. Giving EU authorities a first mover advantage will reduce their share of the total regulation. The unit regulation is considered a "bad" as it distorts the utility-maximising behaviour and thus the rent to be confiscated by the lump sum regulation. Hence, the unit regulation comes with a cost, which both regulators aim at minimizing.

Changing the preferences for one regulator (EU authorities) whilst keeping the preferences of the national authorities and the fisheries organization constant, changes the optimal unit regulation of both regulators markedly. With unequal preferences, the two regulators no longer regard their respective share of the total regulation as strategic substitutes, but rather as strategic complements. This implies that national authorities' response to more aggressive play by the EU authorities will be to play more aggressively. In this situation simultaneous play by the two regulators will give more moderate regulations for both regulators compared to sequential play where the EU authorities set their regulation first.

In a hierarchical management system, as applies to most EU-fisheries systems, unequal preferences typically give rise to so-called implementation drift (Gezelius et al. 2008). This defines a situation where one authority level (e.g. the national authorities) pursue their own interests rather than implementing the regulations set by a superior authority level (e.g. the EU authorities). In this situation unequal preferences for two regulators may lead to a situation where one regulator offers a subsidy whereas the other imposes a tax upon the activity. In such situations, the aggregate unit regulation becomes uncertain. The data we apply to describe fisheries stakeholders' preferences does not indicate significant differences in preferences towards fisheries activities for EU and the member states' national authorities (Aanesen et al. 2014b). This, however, does not mean that such differences are not present in any of the EU-fisheries. Our empirical data on preferences is an average for fisheries stakeholders across eight European countries. In each of the included member states national authorities may have significantly different preferences for fisheries activities compared to the EU fisheries authorities.

There are a couple of other characteristics of the optimal regulations in our model. First, when both regulators agree on either a tax or a subsidy, the aggregate of the two unit regulations is always higher compared to the one the original regulator would set when acting alone. This is true even if the original regulator reduces the unit regulation as a reaction to the introduction of a second regulator. Hence, the reduction in the original regulators' regulation is smaller than the regulation suggested by the new regulator. In other words, although national authorities may react to the EU regulation by reducing their original unit regulation, this reduction will not be sufficient to totally offset the effect of the EU regulation, and the aggregate unit regulation will increase compared to if the fishery were regulated solely by national authorities. Second, the fact that one regulator acts as a leader does not alter the aggregate regulation; it only changes the share of the aggregate regulation carried by each of the regulators.

EU fisheries policy has, since it was first introduced in 1971 and expressed through the CFP, been characterised as a big failure (COM 2009; World Bank 2009). Generous subsidies have resulted in a fishing fleet which is considered to be too large for the commercial stocks in EU waters. The model presented in this paper shows that in a situation where the authorities have relatively equal preferences and want to implement a higher effort level, and thus harvest compared to the fisheries representatives, a two level regulation system reinforces the use of regulations in order to promote effort. This means that when both EU authorities and national authorities regulate the fisheries activities, the aggregate effect of the regulations is stronger compared to if there were only one regulator. This may explain why the EU fisheries subsidies became very large. On the other hand, if it is in the interest of regulating authorities to restrict effort, and thus harvest in the EU fisheries, the two levels of regulatory authorities may be an advantage. Our model shows that in this case, the aggregate effect of the regulations is stricter when there are two regulatory authorities compared to when there is only one. This presupposes relatively equal preferences for the two regulators, but it is independent of whether the regulations are set simultaneously or sequentially.

A crucial characteristic of the model and results presented in this paper is the definition and formulation of preferences. We have applied traditional and relatively simple bio-economic functions to model the preferences, such as the long run single species growth function and the profit function. Concentrating on traditional management of a single species fishery, this is sufficient to demonstrate the effects of including new stakeholders in fisheries management. It could be of interest to extend the environmental preference function in order to take into account aspects of ecosystem based management. This could be done by expanding the long run biological growth function to include fishery-habitat or multi-species interactions, and would enable a more explicit treatment of ecosystem effects, and how this affects optimal regulations. These are tasks left for future research.

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6 Appendix

6.1 Regulators Moving Sequentially

Taking the derivative of U^{EU} in (10) w.r.t. E yields the optimal effort for the EU authorities, which is

$$E_{EU}^{S*} = \frac{r\left[qK\left(\Gamma^{EU} + \lambda\Gamma^{F}\right) - Q^{EU} - \lambda Q^{F} - \lambda w_1^* + \frac{\Gamma^{N} + (1-\lambda)\Gamma^{F}}{\Gamma^{N} + \Gamma^{F}} v_1^S\right]}{2q^2K\left(\Gamma^{EU} + \lambda\Gamma^{F}\right)} \tag{22}$$

The optimal effort level for the national authorities is found by maximising U^N w.r.t. E, and given (11), and is given by

$$E_N^{S*} = \frac{r\left[qK\left(\Gamma^N + \lambda\Gamma^F\right) - Q^N - \lambda Q^F \mp (1-\lambda)\, t_1^S - \lambda v_1^S\right]}{2q^2K\left(\Gamma^N + \lambda\Gamma^F\right)} \tag{23}$$

And the optimal effort for the fishers, given two regulators is

$$E_F^{**} = \frac{r\left[qK\Gamma^F - Q^F - v_1^S - t_1^S\right]}{2q^2K\Gamma^F} \tag{24}$$

Equalising (22) and (24) yields (13) and equalising (23) and (24) yields (14).
The explicit expressions for the optimal regulations are

$$v_1^{S*} = -\frac{\Gamma^{EU}\left(\Gamma^N + \Gamma^F\right)}{\Gamma^F\left(\Gamma^{EU} + \Gamma^N + \Gamma^F\right)} w_1^* + \frac{\left(\Gamma^N + \Gamma^F\right)\left(Q^{EU}\Gamma^F - Q^F\Gamma^{EU}\right)}{\Gamma^F\left(\Gamma^{EU} + \Gamma^N + \Gamma^F\right)} \tag{25}$$

$$t_1^{S*} = \frac{\left(\Gamma^N + \Gamma^F\right)\left(\Gamma^{EU} + \Gamma^F\right)}{\Gamma^F\left(\Gamma^{EU} + \Gamma^N + \Gamma^F\right)} w_1^* - \frac{\Gamma^N\left(Q^{EU}\Gamma^F - Q^F\Gamma^{EU} - \Gamma^{EU}w_1^*\right)}{\Gamma^F\left(\Gamma^{EU} + \Gamma^N + \Gamma^F\right)} \tag{26}$$

6.2 Regulators Moving Simultaneously

The national authorities' optimisation problem in the case of two regulators is now

$$\begin{aligned} max U^N &= \beta_1^N PqKE\left(1 - \frac{qE}{r}\right) + \beta_2^N\left(pqKE\left(1 - \frac{qE}{r}\right) - aE\right) \\ &\quad + \beta_3^N SE + \rho\left(t_0^C + t_1^C E\right). \end{aligned} \tag{27}$$

$$\begin{aligned} \text{s.t.}\quad & \beta_1^F PqKE\left(1 - \frac{qE}{r}\right) + \beta_2^F\left(pqKE\left(1 - \frac{qE}{r}\right) - aE\right) \\ & +\beta_3^F SE - \left(t_0^C + t_1^C E\right) - \left(v_0^C + v_1^C E\right) \geq 0 \end{aligned} \tag{28}$$

$$\dot{X} \equiv \left[F(X) - h(E, X)\right] = 0 \tag{29}$$

were we have kept the same share of the regulation revenue to national authorities, ρ, as in the previous examples.

Taking the derivative of U^N w.r.t. E yields the optimal effort for the national authorities, which is

$$E_N^{C*} = \frac{r\left[qK\left(\Gamma^N + \lambda\Gamma^F\right) - Q^N - \lambda Q^F + (1-\lambda)t_1^C - \lambda v_1^C\right]}{2q^2K\left(\Gamma^N + \lambda\Gamma^F\right)} \tag{30}$$

The optimal effort level for the EU authorities is given by

$$E_{EU}^{C*} = \frac{r\left[qK\left(\Gamma^{EU} + \lambda\Gamma^F\right) - Q^{EU} - \lambda Q^F + (1-\lambda)v_1^C - \lambda t_1^C\right]}{2q^2K\left(\Gamma^{EU} + \lambda\Gamma^F\right)} \tag{31}$$

And the optimal effort for the fishers, given two regulators is

$$E_F^{**} = \frac{r\left[qK\Gamma^F - Q^F - v_1^C - t_1^C\right]}{2q^2K\Gamma^F} \tag{32}$$

The explicit expressions for the optimal regulations when there are two regulators are:

$$t_1^{C*} = \frac{Q^N \Gamma^{EU} - Q^{EU} \Gamma^N + Q^N \Gamma^F - Q^F \Gamma^N}{\left(\Gamma^{EU} + \Gamma^N + \Gamma^F\right)} \tag{33}$$

$$v_1^{C*} = \frac{Q^{EU} \Gamma^N - Q^N \Gamma^{EU} + Q^{EU} \Gamma^F - Q^F \Gamma^{EU}}{\left(\Gamma^{EU} + \Gamma^N + \Gamma^F\right)} \tag{34}$$

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