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Balancing biological and economic goals in commercial and recreational fisheries: systems modelling of sea bass fisheries

Hannah J. Tidbury [1,*], Angela Muench [2,3], Philip D. Lamb [2], and Kieran Hyder [2,3]

[1]Centre for Environment, Fisheries and Aquaculture Science, Weymouth DT4 0AB, UK
[2]Centre for Environment, Fisheries and Aquaculture Science, Lowestoft NR33 0HT, UK
[3]School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, Norfolk NR4 7TJ, UK

*Corresponding author: tel: +44 130 520 6764; e-mail: hannah.tidbury@cefas.co.uk.

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The importance of social and economic factors, in addition to biological factors, in fisheries management is being increasingly recognised. However, exploration of trade-offs between biological, social, and economic factors under different sustainable catch limits for recreational and commercial fisheries is limited, especially in Europe. The European sea bass (*Dicentrarchus labrax*) is valuable and important for both commercial and recreational fisheries. Stocks have rapidly declined and management measures have been implemented, but trade-offs between social, biological, and economic factors have not been explicitly considered. In this study, a system dynamics model framework capturing biological and economic elements of the European sea bass fishery was developed and refined to incorporate a catch limit reflecting sustainable fishing with adjustable partition between recreational and commercial sectors, under low, medium, or high recruitment. Model outputs were used to explore the relative impact of different catch allocations on trade-offs between biological sustainability and economic impact when recruitment was limiting or not. Recruitment had a large impact on the fish population dynamics and the viability of the sectors. At high and moderate recruitment, management contributed to stock sustainability and sector economic impact, but recruitment is important in determining the balance between sectors.

Keywords: bioeconomic model, European sea bass, fisheries management, integrated assessment, system dynamics

Introduction

Marine governance, such as the EU Common Fisheries Policy (CFP) (EU, 2013) and United Nations Convention on Biological Diversity (CBD, United Nations, 1992) mandates the need for an ecosystem approach to marine management that promotes conservation and sustainable use in an equitable way. For example, the CFP includes an ecosystem approach and states that access to a fishery should be based on transparent and objective criteria including those of an environmental, social, and economic nature (EU, 2013). Furthermore, the three objectives of the CBD are conservation of biodiversity, sustainable use, and equitable sharing of benefits (United Nations, 1992). Government and stakeholder involvement in management decisions, implementation, and enforcement through fisheries co-management presents a promising approach to achieving sustainable fisheries (Pinkerton, 1989; Plummer and Fitzgibbon, 2004). However, though crucial, there remain few examples where fisheries management includes a transparent and balanced consideration of the biological, social, and economic elements of both commercial and recreational fisheries (Cooke and Cowx, 2004; ICES, 2020).

The European sea bass is widely distributed across the north-east Atlantic (Pickett *et al.*, 1994) and is divided into four stocks for management purposes. The northern stock, which is found in the Irish Sea, Celtic Sea, English Channel, and southern North Sea (ICES, 2018a) is characterised by relatively slow-growing individuals that tend to reach maturity between the age of 4 and 7 and have a maximum lifespan of 30 years (Pawson and Pickett, 1996). In the northern stock, mature individuals aggregate to spawn between February and June (Pawson and Pickett, 1996). The pelagic larval phase lasts for at least 30 days (Jennings and Pawson, 1992), allowing dispersal to nursery grounds that are located in sheltered coastal sites such as estuaries, harbours and saltmarshes (Pawson and Pickett, 1996). After spending the first few years of life in the nursery grounds, juveniles migrate offshore to join the adult population (Pickett *et al.*, 2004). The northern sea bass stock has suffered a severe decline over the past decade, that has been attributed to poor year-class strength, as a result of unfavourable environmental conditions and increasing fishing pressure (de Pontual et al., 2018). Effective management is central to ensuring the sustainable exploitation of the sea bass stock (Ares, 2016a, b; ICES, 2012). Prior to 2015, management measures focused on a minimum conservation reference size and, in the United Kingdom (UK), protection of juvenile nursery habitats (Pawson *et al.*, 2005). Emergency measures, including the banning of offshore mid-water trawling for sea bass, were introduced by the European Commission in 2015 to conserve the stock. Since 2016, management measures have been implemented to add further protection including seasonal closures, increased Minimum Conservation Reference Size for both commercial and recreational fisheries, monthly or annual catch limits for the commercial fishery, and bag limits for the recreational fishery (Ares, 2016a, b; EU, 2017; de Pontual *et al.*, 2019; ICES, 2018a).

Fishing pressure is from a combination of commercial and recreational fisheries, with the impact of recreational fishing on fish stocks, such as sea bass, becoming increasingly recognised (Cooke and Cowx, 2004; Ihde *et al.*, 2011; Hyder *et al.*, 2018a, b; Radford *et al.*, 2018; Lewin *et al.*, 2019). Recreational catches were estimated to be in the region of 27% of total sea bass commercial and recreational removals in 2012 for the northern stock (Hyder *et al.*, 2017, 2018a,b; Radford *et al.*, 2018). Given the fishing pressure exerted by recreational and commercial fisheries, sustainable management of fisheries requires consideration of removals by both sectors, and allocation decisions to be made (Hyder *et al.*, 2014, 2017, 2018a,b). There are two potential approaches: implicit and explicit allocation. Implicit allocation occurs where management drives the catch share allocated to each sector. Explicit allocation is where a catch share is set for commercial and recreational fisheries then management is implemented to achieve it. Catch allocation between the recreational and commercial sectors in Europe has been implicit (e.g. sea bass, western Baltic cod). Explicit allocation decisions are made in other countries, for example for the Gulf of Mexico red snapper fishery (Abbott and Willard, 2017), The Gulf of Maine North Atlantic Groundfish fishery (e.g. Atlantic cod, haddock) (NEFMC, 2003), and in Western Australia (e.g. western rock lobster, metropolitan Roes abalone) (Crowe *et al.*, 2013) and New Zealand (e.g. marlin, kingfish, kahawai, and snapper) (Fisheries Act, 1996). However, these decisions are rarely transparent, with limited consideration of the trade-offs between economic, social, and biological benefits under different allocations between the recreational and commercial sectors, especially in Europe (ICES, 2020).

System dynamics modelling is implemented to understand the dynamic behaviour of often complex systems over time, with a focus on understanding how feedback loops determine the system behaviour which results from a given system structure (Sterman, 2002). System dynamics modelling incorporates stocks, flows, feedback loops, and time delays (Forrester, 1997). The approach includes visualisation of key links between different elements of a system and enables understanding of the behaviour of systems by individuals from different disciplines and sectors. This type of modelling has been applied across social, management, economic, and environmental sectors. While some examples of the application of system dynamics modelling to fisheries management do exist (e.g. Moxnes, 2000; Dudley, 2008; Garrity, 2011; Lee *et al.*, 2017), system dynamics has not previously been applied to inform sea bass fisheries management, in particular with respect to partition of catch limits between recreational and commercial sectors, and marine policy decisions.

In this study, a system dynamics model is developed and applied to the management of the European sea bass stock. Initially, a framework which captures key biological and economic elements of the European commercial and recreational sea bass fishery is developed and parameterised. Model outputs are then calibrated against ICES stock assessment data. The model is refined to incorporate a catch limit reflecting sustainable fisheries management, with adjustable partition between recreational and commercial sectors, under scenarios of low, medium, or high recruitment. Model outputs are used to explore the relative merit of different partition scenarios with respect to trade-offs between biological sustainability and economic impact, when recruitment is limiting or not. The results are discussed in the context of future management of the European sea bass.

Model framework

Model development

The model represents the biological and economic elements of a simplified sea bass only fishery, incorporating feedbacks and links considered most important for the dynamics of the sea bass population, commercial fisheries, and recreational fisheries (Figure 1). For full technical specification of the model, parameter values and sensitivity analyses see Supplementary material.

The model was developed and examined using a system dynamics approach. However, to aid transparency and interpretation, key relationships are also presented in the form of difference equations (see Supplementary material). The spatial remit of the model follows the stock definition used in the assessment (ICES, 2019). Hence, it applies to the whole of the Northern Stock which is defined as covering the central and southern North Sea (ICES areas IVb&c), the Channel (ICES VIId&e), parts of the Celtic Sea (ICES areas VIIf-h), and Irish Sea (ICES VIIa). The main countries covered in the assessment are UK, France, Belgium, and Netherlands (ICES, 2019). Where possible, model parameters are based on data for sea bass in ICES Divisions IVb&c, VIIa, and VIId-h. If data represented UK waters only, they were used as a proxy and scaled up where necessary to reflect for the whole region.

Sea bass stock population

The modelled sea bass population is split into two; juvenile fish (age 0–5 years), and adult fish (age 6–30 years) (Figure 2). Replenishment of juvenile stock depends on annual recruitment. Juvenile and adult fish are lost to natural mortality. Adult fish are also lost as a result of commercial catch driven by commercial fishing pressure, and recreational catch driven by recreational fishing pressure. A proportion of the recreational catch is released and survives, therefore returning to the adult population.

Commercial fishing activity

The number of commercial fishing trips represent commercial fishing activity. The number of commercial fishing trips is translated into effort [days at sea (DAS)], which when multiplied by

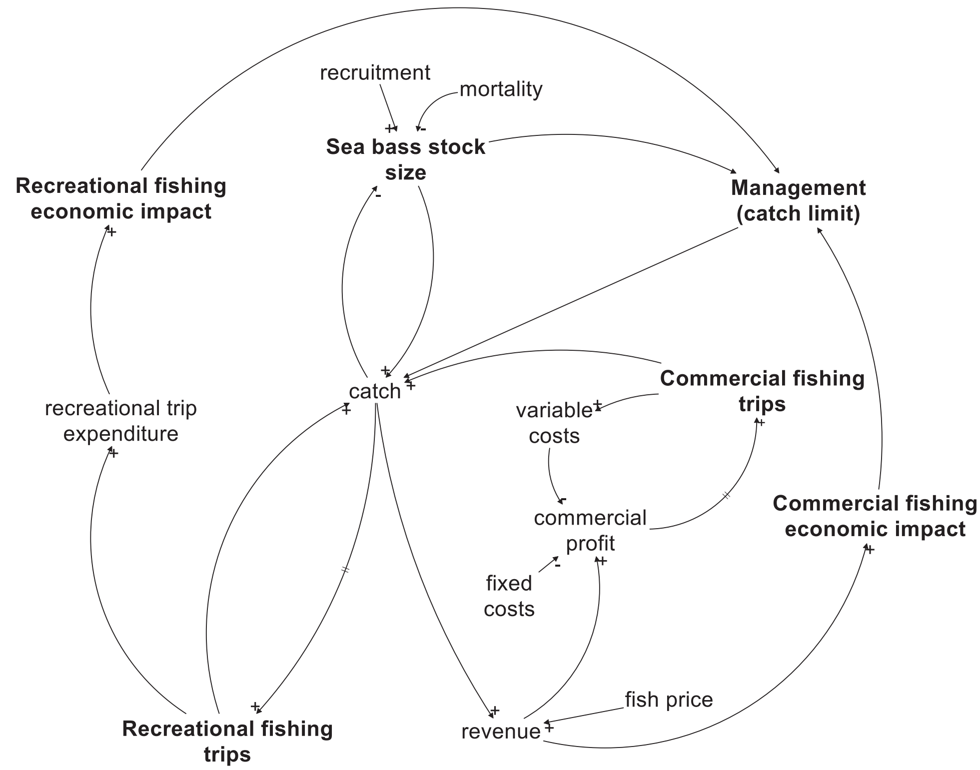

Figure 1. Causal loop diagram, illustrating the key elements and variables which are important in the sea bass system and their links and feedbacks. Plus and minus symbols represent positive and negative feedbacks, respectively.

commercial catchability is used to determine the commercial fishing pressure. Commercial fishing pressure (and adult stock size) determines the amount of commercial catch.

The weight of commercially landed fish is estimated from total catch, accounting for the proportion of the commercial catch which is discarded [estimated to be 5% (ICES, 2016b; Radford *et al.*, 2018)] and the average weight of landed fish. Commercial discard survival is assumed to be zero so that no discarded commercial catch returns to the adult population. Commercial revenue is estimated from the multiplication of the weight of commercially landed fish by the sales unit price.

Change in commercial fishing activity is influenced by commercial profit which is estimated by subtracting commercial fishing costs from the commercial fishing revenue. Commercial fishing costs are split into variable costs and fixed costs. Variable costs reflect costs associated with each fishing trip, such as staff and fuel costs per DAS. Fixed costs are estimated by taking a proportion of the total fixed costs, incurred for maintenance of the vessels and equipment used for commercial sea bass fishing, to account for the fact that the vessels and equipment may be used to target other species in addition to sea bass. The proportion used reflects that, on average, approximately 40% of the commercial under ten feet targets bass (STECF, 2017). Feedback between commercial profit and commercial fishing trips is such that, if profit is made, the number of fishing trips will increase by a fixed proportion until the maximum number of trips is reached. If profit is not made, the number of fishing trips will reduce by a fixed proportion. To account for the likely delay in feedback between profit and commercial fishing effort, it is profit 2 years previously, which drives change in the number of commercial fishing trips.

Gross Value Added (GVA), as a result of commercial fishing activity, is estimated from commercial revenue using a multiplier based on the estimated proportion of this revenue which contributes to GVA (STECF, 2017), and is indicative of economic impact.

Recreational fishing activity

The number of recreational fishing trips reflects the recreational fishing activity. Similar to commercial fishing trips, the number of recreational fishing trips is translated into effort (fishing days), which when multiplied by recreational catchability is used to determine the recreational fishing pressure. Recreational fishing pressure (and adult stock size) determines the recreational catch.

Recreational fishing activity is influenced by recreational catch per unit effort. Specifically, feedback between catch per unit effort and number of recreational fishing trips for sea bass is such that, if catch per unit effort is greater than a set threshold, the number of recreational fishing trips will increase by a fixed proportion if below the maximum number of trips set, and if at the maximum number of trips set will stay the same. If the recreational catch per unit effort is below the threshold set, then the number of recreational fishing trips will reduce by a fixed proportion. Catch per unit effort 1 year previously drives change in the number of recreational fishing trips.

Gross value added (GVA), as a result of recreational fishing activity, is estimated from the trip expenditure (e.g. bait, fuel, food, and drink) by using a multiplier based on the estimated proportion of this trip expenditure which contributes to GVA (Armstrong *et al.*, 2013; Roberts *et al.*, 2017), and is indicative of economic impact.

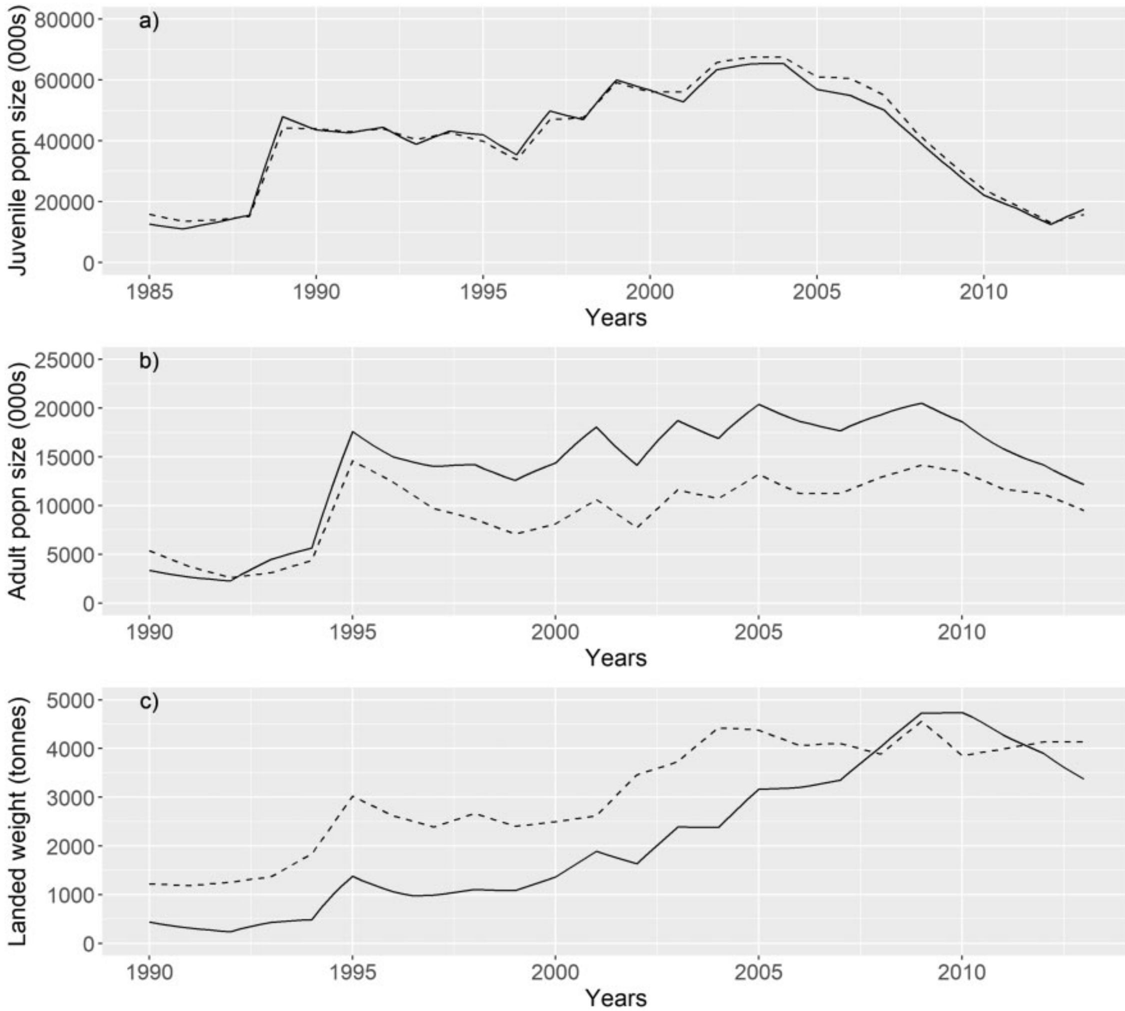

Figure 2. (a) Juvenile (age 0–5) stock size, (b) adult (age 6–30) stock size, and (c) commercial landings weight from ICES stock assessment (ICES, 2015) (dashed) and model outputs (solid). Adult stock size and landings weight is reported from 1990, the first year for which adult size is influenced by recruitment data input into the model.

Parameterisation and calibration

The baseline model is parameterised and calibrated to reflect dynamics documented for ICES divisions IVb&c, VIIa, and VIId-h. Given the lack of available data, in particular in relation to economics for non-UK countries (e.g. France, Belgium, Netherlands, and Channel Islands), the model is parameterised primarily using UK data (Supplementary Table S1). Data for the UK commercial fishery indicates that since 2008 the under 10 m commercial fleet is responsible for about 90% of sea bass landings (MMO, 2018), therefore, commercial fishing model parameter estimates are based on figures for the under 10 m fleet. A number of different sources were used to parameterise the model, including sea bass stock assessments, and working group reports (ICES, 2015, 2016a, 2018a) for the biological parameters, the Annual Economic Report on the European Fishing Fleet (STECF, 2017) and sales notes for the commercial fishing sector (MMO, 2018), as well as information derived from surveys for the recreational fishing sector and logbooks (Hyder *et al.*, 2020). The number of UK commercial trips for sea bass is estimated from: the proportion of trips which practice methods and use equipment associated with sea bass fishing; and for which sea bass is listed in the top five landed species. This is scaled up to reflect the whole fleet (including non-UK countries) using the estimated proportion of total landings which are UK (ICES, 2018a) as a proxy. The number of recreational fishing trips is estimated from the number of recreational fishing trips which landed sea bass in 2012 in England (Armstrong *et al.*, 2013) scaled up to reflect the size of the sector across the whole region. Where data from multiple years were available, mean values were used. The baseline model was run using historical recruitment estimates from 1985 to 2013 (ICES, 2018a). Parameter values and sources can be found in Supplementary Table S1.

Model outputs, primarily juvenile, adult population size, and commercial landings were compared to stock assessment outputs to check that model output trends and ranges were as expected for the parameter values used.

Fishery management and partition between the commercial and recreational sector

Sustainable management is implemented in the model through the addition of a "catch" limit. Note that when applied to the commercial fishing sector, this limit represents a landing limit, and when applied to the recreational fishing sector the limit refers to a retainment limit. The limit is dynamic and calculated according to the Baranov catch equation (Baranov, 1918). Specifically, it is estimated as a function of adult population size, natural mortality, and fishing pressure which gives Maximum Sustainable Yield (F_{MSY}) (ICES, 2018a). Juvenile and adult mortality was increased to reflect changes in mortality estimates used in stock assessments (Then *et al.*, 2015; ICES, 2018a) and calculation of F_{MSY}.

The biomass available under F_{MSY} is partitioned between commercial and recreational sectors under various scenarios (Supplementary Table S2). We include five partitioning scenarios ranging from full allocation to one or the other sector, to an equal split between the two sectors, as well as a no fishing scenario and a no catch limit (no management) scenario. For each scenario, stock biomass is examined under high, medium, and low fixed recruitment (reflecting the 5th percentile, median, and 95th percentile of 1985 to 2013 recruitment estimates from the ICES assessment), and fishing activity and GVA for the two sectors is calculated. Absolute and relative values are reported. For relative comparisons, the catch partition in 2012 (around 75% commercial, 25% recreational allocation) (Armstrong *et al.*, 2013; Hyder *et al.*, 2017, 2018a,b; Radford *et al.*, 2018) is used as the baseline before the introduction of management measures in 2015.

Commercial catch above the catch limit is discarded, and discard survival is assumed to be zero (as in the baseline model). Given the potentially higher rate of discard under management, the impact of discard survival was considered but was found to be minor on overall trends due to the feedback between population size and catch limit. For the scenario which allocates the full limit to the recreational fishing sector, commercial fishing trips are set to zero to reflect the assumption that targeting of sea bass by the commercial sector will cease.

Recreational catch is retained at the same rate as for the baseline model until the retainment limit is reached. All catch above the retainment limit is released. For the scenario which allocates the full limit to the commercial sector, the recreational fishing sector operates on a catch and release only basis. A linear reduction in maximum number of recreational trips, corresponding to the allocation of limit to the recreational fishing sector, is included in the model. Specifically, when the full limit is allocated to the recreational fishing sector, the reduction in maximum recreational fishing trips is zero, increasing as the recreational allocation drops so that when the full limit is allocated to the commercial fishing sector, the reduction in maximum number of recreational fishing trips is 25%. This reflects the assumption that for in the region of 25% of recreational anglers which target sea bass, retainment is important [informed by reports of 77% recreational release rate for England (Ferter *et al.*, 2013)], with measures that restrict and prohibit retainment, impacting their fishing experience satisfaction. A no-fishing scenario is implemented by setting commercial and recreational trips to zero. A no management scenario is implemented by removing trip limits.

Results

Calibration

Outputs from the model followed the trends seen in the ICES sea bass stock assessment, indicating that the model structure reflects the sea bass fishery (Figure 2). In particular, the peak in juvenile stock around the years 1989 and 2003, and adult stock around 1995 evident from the stock assessment was echoed in the model outputs (Figure 2a and b). In the model, commercial landings were strongly dependent on the adult stock population so that, at a given fishing pressure, landings were proportional to the sea bass adult stock population (Figure 2c). In reality, the relationship between commercial landings and stock, in the absence of management, is likely to be more complex.

Fishery management and partition between commercial and recreational sector

Model outputs were strongly affected by recruitment as well as by controls imposed on the fishery. The size of the sustainable catch limit, driven by population size and therefore recruitment, affected how different levels of partitioning impact the recreational and commercial sectors (Figure 3, Table 1).

Firstly, in the case of constant low recruitment, the sea bass population, along with both the commercial and recreational fishing sectors, would collapse [Figure 3, Table 1 (low)]. The small and declining sea bass population resulting from low recruitment [Figure 3a (low)] would lead to a reduction in a commercial and recreational activity, through a reduction in profit and catch per unit effort respectively, regardless of the allocation of catch limit to the sectors. The recreational fishing activity would decline through time at the same rate, regardless of the catch limit allocation scenario, as would recreational GVA [Figure 3c and f (low)] as it is attributed to trip expenditure. The relative difference in recreational activity and estimated economic impact between the baseline partition scenario (75% commercial, 25% recreational) and other partition scenarios, was therefore zero [Table 1, (low)]. The commercial activity would also decline through time across all scenarios. However, due to a slight increase in commercial fishing trips, based on profitable landings, under 100% allocation of catch limit to commercial sector scenarios, commercial activity would be slightly higher in early years [Figure 3b (low)], which through respective changes in landings would translate into slightly increased commercial GVA [Figure 3f, (low)]. The commercial activity was ~30% greater under the 100% partition to commercial sector scenario, compared to the baseline partition scenario. In the absence of fishing pressure, the population would eventually decline to a similar size as under a *no management* scenario, albeit more slowly [Figure 3a (low)], further demonstrating that the sea bass population dynamics seem to be the consequence of low recruitment and largely independent of fishing pressure.

Under constant medium recruitment, a *no management* scenario would result in cyclic commercial fishing activity, and consequently oscillatory population dynamics [Figure 3a and b (medium)]. Such dynamics occurred when the commercial industry was operating close to its profit threshold. A loss of commercial profit would lead to a reduction in commercial fishing activity, which in turn would lead to an increase in the sea bass population. This increase in population size resulted in increased landings, with associated increase in profit, with a knock-on increase in commercial fishing activity, which then acted to reduce the population, causing reduced profits and a decline in activity. In addition, under medium recruitment, differential sustainable catch allocation between the two sectors would have strong implications. Intuitively, allocation of the total limit to the commercial sector would allow increased commercial landings, greater profit,

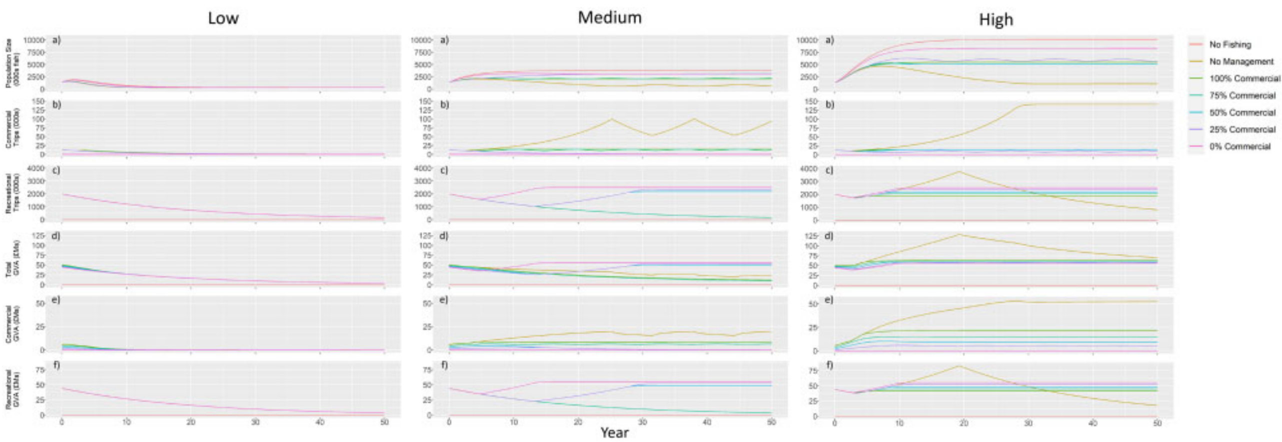

Figure 3. Model outputs for the sea bass population, and recreational and commercial fishing activity and impact (top to bottom), under low, medium, and high recruitment (left to right). The years are presented to illustrate the differences in dynamics generated by the model, but the end of the time series was used for interpretation as this represents the long-term outcome.

Table 1. Relative sea bass population, and recreational and commercial fishing activity and impact model outputs at 50 years, under low, medium, and high recruitment.

			Model outputs year 50					
				Activity		GVA		
Scenario			**Population size**	**Commercial**	**Recreational**	**Total**	**Commercial**	**Recreational**
Recruitment	High	No fishing	1.99	0.00	0.00	0.00	0.00	0.00
		No management	0.22	10.00	0.39	1.17	3.54	0.39
		100% commercial	1.08	1.00	0.92	1.06	1.47	0.92
		75% commercial	1.00	1.00	1.00	1.00	1.00	1.00
		50% commercial	0.99	1.00	1.08	0.97	0.63	1.08
		25% commercial	1.12	0.67	1.15	0.95	0.34	1.15
		0% commercial	1.63	0.00	1.23	0.93	0.00	1.23
	Medium	No fishing	1.71	0.00	0.00	0.00	0.00	0.00
		No management	0.28	7.95	1.00	2.31	3.02	1.00
		100% commercial	0.94	1.20	1.00	1.17	1.26	1.00
		75% commercial	1.00	1.00	1.00	1.00	1.00	1.00
		50% commercial	1.43	0.01	13.54	4.81	0.01	13.54
		25% commercial	1.41	0.01	14.50	5.15	0.01	14.50
		0% commercial	1.40	0.00	15.47	5.48	0.00	15.47
	Low	No fishing	1.03	0.00	0.00	0.00	0.00	0.00
		No management	1.00	1.30	1.00	1.00	1.28	1.00
		100% commercial	1.01	1.30	1.00	1.00	1.30	1.00
		75% commercial	1.00	1.00	1.00	1.00	1.00	1.00
		50% commercial	1.00	1.00	1.00	1.00	1.00	1.00
		25% commercial	1.00	1.00	1.00	1.00	1.00	1.00
		0% commercial	1.01	0.00	1.00	1.00	0.00	1.00

The 2012 catch share (75% commercial, 25% recreational allocation) is used as the baseline for relative comparisons, which was before the introduction of management in 2015.

and the commercial sector to operate at the capacity (trip) limit set in the model [Figure 3b (medium)]. However, only a 25% drop in allocation to the commercial sector would result in cyclic dynamics [Figure 3b (medium)]. These dynamics were likely driven by the same feedbacks between landings, profit, and trips as for a no management scenario, rather than the result of population size. When the allocation of the landing limits to the commercial sector was set to 50% or less, the commercial sector would no longer be profitable, with consistent loss of fishing activity over time, despite an increase in sea bass population size [Table 1 (medium)]. Allocation of the total catch limit to the commercial sector would result in up to a 20% increase in the commercial activity, with 26% increase in GVA when compared to the baseline allocation scenario. However, model outputs also suggested up to a 25% drop in population size with greater than equal allocation of the catch limit to the commercial sector [Table 1 (medium)]. The recreational fishing industry would collapse under no management, and greater than 50% allocation of the catch limit to the commercial sector under medium recruitment [Figure 3c (medium)]. This was caused by the low level of sea bass population and a resulting catch per unit effort below the threshold set. Under favourable allocation of catch limit to the recreational industry (50% or greater), the sea bass population would increase and support a viable recreational industry [Figure 3c (medium)].

Under constant high recruitment, a no management scenario would result in high levels of the commercial fishing activity and a relatively low population size [Figure 3b (high)]. While the recreational industry would also be initially strong, the recreational fishing activity would decline from around year 20 [Figure 3c (high)]. This seems to be a consequence of the reduced sea bass population size which would result from heavy commercial fishing pressure. An allocation of greater than 50% of the limit to the commercial sector, would allow it to operate at the maximum capacity set [Figure 3b (high)]. Reduction of allocation to the commercial sector to 25% would result in cyclic dynamics where the allocated limit would mean that the commercial sector would be operating very close to its profit threshold [Figure 3b (high)]. Due to high catch per unit effort, resulting from a large sea bass population, the recreational industry would be stable under each allocation scenario. Even when the recreational fishery receives 0% of the catch limit allocation, it may remain economically viable as a catch release only fishery (Table 1) albeit on a smaller scale than when it received some catch limit allocation. Under high recruitment, the relative difference seen between each allocation scenario and the baseline allocation scenario was much reduced compared to under medium recruitment [Table 1 (high)].

The outputs from the model highlighted trade-offs between biological sustainability and economic impact. Under high recruitment, the economic impact was greatest when the population size was lowest, i.e., under a no management scenario [Figure 2, Table 1 (high)]. Despite the large reduction in recreational GVA, profitable commercial landings, supported by such a large population, drive this high total GVA. Under high recruitment, there are multiple allocation scenarios which would allow a viable commercial and recreational sector to exist in parallel, with the 50% allocation to each sector or 75% commercial and 25% recreational allocation providing favourable balance between the economic impact of each sector and the population size [Figure 2, Table 1 (high)]. Under medium recruitment, none of the allocation scenarios tested resulted in the long-term viability of recreational and commercial fisheries [Figure 2, Table 1 (medium)]. Greater than or equal to a 50% allocation to the recreational sector resulted in a viable recreational industry, while the commercial industry was only viable when it received a 75% or greater partition of the allocation. Under medium recruitment, the no management scenario produced the lowest population size but did not produce the greatest GVA (Figure 2, Table 1 (medium)). This was the consequence of the loss of the recreational industry, following a reduction in population size under no management and a catch per unit effort value below the threshold.

Discussion

Effective management would ideally maximize opportunities and GVA for commercial and recreational fishing sectors, which contribute significantly to the UK and the European economy, while preventing stock depletion and ensuring biological sustainability. This study developed and implemented a system dynamics model which represents a simplified and stylised sea bass fishery, incorporating the sea bass stock population and both recreational and commercial sectors. By implementing a sustainable catch limit with adjustable allocation to recreational and commercial sectors, the model provides a tool which can be used to evaluate the relative biological and economic impacts of different allocation scenarios. Despite the need for caution to be exercised when interpreting outputs, due to data limitations, the model created provides a promising tool to inform the development of catch allocation schemes in the future.

Given the social and economic impact of the commercial and recreational fishing industries, management approaches which support both are desirable, if possible. Outputs from this model indicated that balancing both sectors within a sustainably managed fishery would not be straightforward. For example, only under high recruitment do some of the scenarios modelled enable viable commercial and recreational sectors to occur in parallel with a sustainable sea bass population. Model outputs demonstrated a strong influence of recruitment on management outcomes. For example, our model showed that under low recruitment, as observed since 2010, stock recovery would be very slow and $B_{lim,}$ would not be achieved (ICES, 2018b) even with the implementation of zero catch management, a conclusion also drawn by ICES (2019). While perhaps intuitive, such influence of recruitment on the potential outcome of management highlights the need to further our understanding of stock recruitment. It is well accepted that environmental conditions and climate play an important role in the recruitment of a number of fish species including herring (Groger *et al.*, 2010), cod (Brander, 2005), sole (Henderson and Seaby, 2005), whiting (Cook and Heath, 2005), and sea bass (Pawson *et al.*, 2000; Beraud *et al.*, 2018). While progress has been made towards understanding such relationships in sea bass, there remains uncertainty around forecasting year-class strength (e.g. Subbey *et al.*, 2014).

Using fixed recruitment, reflecting low, medium, and high historical values, we provided insight into, and facilitated comparison of, management outcomes under a worst-, intermediate-, and best-case scenario. However, while eliminating feedback between the population and recruitment facilitated more accessible outputs and easier interpretation, it likely created a system with more stability than would be observed in nature. For example, when the commercial sector was operating close to its profit threshold, the sea bass population entered cyclic dynamics. This could be tested by implementing a stochastic recruitment function in the model based on the information from pre-recruit surveys. Feedback between population size and recruitment may amplify such cyclic behaviour and, given delay in feedback between commercial profit and commercial fishing activity, may lead to even greater disparity between fishing effort and sustainable limits with consequences to the sea bass population and the commercial sector. A large proportion of the recreational catch is assumed to be released so that an increase in allocation of sustainable catch limit to the recreational sector may increase fishing activity, with associated economic gain. While in our model, we assumed that 75% of the catch is returned (Armstrong *et al.*, 2013) at a 95% survival rate (Lewin *et al.*, 2018), recent management has increased release rate through bag limits, closed seasons, and increased Minimum Conservation Reference Sizes, so this may not reflect current reality and should vary dynamically with management. In addition, increased recreational fishing may change the proportion of gear types used (e.g. lures compared to bait) impacting the levels of post-release mortality (Lewin *et al.*, 2018).

Comparison of short- and long-term outputs from the model highlights the need for predictive tools and emphasise how short-term changes in response to management strategies may be misleading [such observation also supported by Mardle and Pascoe (2002)]. For example, initially under medium recruitment, model outputs indicate similar outcomes under 25–75% partition to the commercial sector in terms of biological sustainability. However, only a few years following implementation, it becomes apparent that the population would be almost twice as large under scenarios with 50% and 25% partition to the commercial sector, compared to 75% partition to the commercial sector. In some instances, parameterisation of the model was only possible using UK data as these were the only data available or accessible. While validation of model outputs against ICES data indicated that the model reflects the system well, data collected for commercial and recreational sectors in other relevant countries (e.g. France, Belgium, and the Netherlands), which for example, may differ in the relative contribution of the commercial and recreational sector to fishing mortality (Radford *et al.*, 2018), would offer opportunity to examine differences and determine potential impacts with respect to catch allocation outcome.

Model parameters were estimated using historical data. Parameters were not expected to change substantially in the short-term; however, changing parameters should be considered when interpreting long-term dynamics. This could be due to environmental change affecting recreational fisheries (e.g. Townhill *et al.*, 2019) or dynamic changes in the parameters due to other externalities (e.g. fish price, supply etc.). For example, advances in fishing technology would likely reduce costs while increasing catchability. Such advances would have consequences on the key commercial feedback in the model, between commercial revenue and activity. Further, we used a fixed market price for sea bass as well as a constant demand over time based on the assumption that the potential for imports of farmed fish or other substitutes will meet the demand and keep the market stable. It is possible that in the absence of imported farmed fish or other substitute fish the market price would follow a supply–demand function, so that when sea bass catch (supply) is high, the price decreases to adjust the supply to the demand assumed to be constant. In turn, when catch is low the price increased under a similar assumption. Such a function may act to buffer the impact of reduced stocks sizes on the commercial fishing sector (Fryxell *et al.*, 2017). However, evidence suggests, at least for sea bass, assuming a fixed price accurately captures market dynamics (EOMOFA, 2018).

Fisher behavioural responses are integral to management outcomes. By modelling a sea bass only fishery, without differentiation of commercial gear type, we did not account for switches in target species and gear type as a response to management measures (e.g. Christensen and Raakjær, 2006; Fulton *et al.*, 2011; Kasperski and Holland, 2013), but rather stick with the notion that fishermen are likely to stay on past trajectories of behaviour (Holland and Sutinen, 2000). Clearly, while fishing activity targeting sea bass may decrease with sea bass management, changing to an alternative species would be likely to facilitate the continuation of a profitable sector (e.g. Cline *et al.*, 2017). The commercial inshore sea bass fleet uses a variety of gears, particularly rod and line, longline, and gillnets. We assumed a discard survival of zero, a worst-case approach, in the absence of robust discard survival estimates for sea bass (ICES, 2018a). However, it is known that gear has a strong impact on discard survival (Catchpole *et al.*, 2015), with knock-on impacts of gear switches on discards likely. A recent study showed that sea bass management measures resulted in a complete change of focus by commercial fishers in the South West of England from sea bass to whelks, crabs, cuttlefish, and wrasse, none of which were covered by quotas (Williams and Carpenter, 2019).

Consumption orientation can be an important motivation for recreational anglers (e.g. Aas and Vittersø, 2000) and recreational catch can provide an important food source (Cooke *et al.*, 2018). Choice experiments have been used to assess sea anglers' willingness-to-pay under different measures managing sea bass in the UK. Results have shown that a significant proportion of anglers preferred to keep their catch compared to 'catch and release' (Brown *et al.*, 2019; Andrews *et al.*, in review). The current model focuses on rod and line angling, which is the main recreational gear type used for sea bass, but should be extended to capture the diversity of gears, particularly spearfishing. While the wider implications of allocation decisions, and more generally sea bass management, are important, the purpose of this study was to examine and provide a greater understanding of the implications with respect to sea bass only. Development of the model, to include details such as gear types (commercial and recreational sector) or angler's motivation, provides a valuable opportunity to determine the impact of different allocation scenarios between the recreational and commercial sector while accounting for commercial fishing gear switching behaviours, and would offer a sensible next step. For example, the multi-criteria decision analysis framework developed by Williams *et al* (2018) facilitates management decisions with respect to partition of catch allocation between different gear types, so that a combination of our model and this could facilitate allocation decisions per sector, and with respect to the commercial sector, per gear type. A similar matrix would need to be found to account for the heterogeneity of anglers' motivation to participate in angling for seabass or switching gear/target species.

Similar to commercial fisheries, recreational fisheries may provide food, economic and social value, and are for many species, a growing source of fishing mortality (EFTEC, 2015; Abbott *et al.*, 2018). Due to data limitations, the current model compares the economic impact of the commercial and recreational sectors, which can be misleading. An extension of the model with regards to total economic value of each sector would be beneficial, if data would be made available.

Management of fisheries for sea bass in the North Sea, Channel and Irish Sea have not been based on a system of Total Allowable Catches, and controls have been based on spatial and seasonal closures, restrictions on fishing methods, minimum conservation reference sizes and limits on catches of individual commercial boats or recreational fishers (ICES, 2012, 2016b). For the latter, seasonally varying individual daily bag limits (in some instances zero fish) were set to try and achieve desired changes in fishing mortality. The only means of monitoring the effectiveness of such bag limits is through recreational fishing surveys. There is therefore potential for retention to be greater than intended, due to insufficient control of fishing effort at the whole sector level (Abbott, 2015).

Evidence-based decisions regarding the allocation of catch between both recreational and commercial sectors are rare, often a consequence of limited or non-standardised data regarding recreational fisheries (Eero *et al.*, 2015; Hyder *et al.*, 2017, 2018a,b). Further, the success of management through the allocation of limits to both sectors requires that the commercial and recreational sectors, are regulated with enforcement implemented when necessary (Potts *et al.*, 2020). However, the larger number and greater dispersal of recreational anglers makes enforcement more challenging and resource intensive. While the present study is not able to address challenges, for example, associated with enforcement and accounting, it provides a method by which the recreational sector can be explicitly incorporated into management decisions.

The model assumed that fishers were targeting sea bass, that there are catch thresholds that limit the numbers of trips, and that they belong to a single fleet. However, sea bass is often not the main target of a trip and is caught whilst targeting other species. While there is merit to modelling a multi-species and multi-fleet fishery explicitly, the data were not available to parameterise such an approach. Furthermore, the scope of the model was to provide insight into the relative impact of different partition between the recreational and commercial sector, which was aided by the simplicity of using a single species approach. Prior to its application to support management, further work is needed to test the impact of relaxing some of the key assumptions and parameters. This could be done through the application of this approach in conjunction with other models (e.g., multispecies) or ensemble-model frameworks. Despite these caveats, the model still provides useful insight into potential impacts of management and highlights the trade-offs between biological and economic elements of the system. The model presented here provides a tool which can be used, in combination with other methodologies and information sources, to inform policy decisions with respect to sea bass management, specifically with respect to the partition of management between the recreational and commercial sector. The geographical scale over which the model can be applied is flexible. It may provide insight into biological and economic impacts of allocation of sustainable catch between recreational and commercial sectors across all broad regions or a more refined insight or comparison across smaller geographical regions.

Coupled with policies documenting clear aims and objectives, in which allocation decisions are embedded, the model developed here has the potential to contribute a vital component to sea bass fishery management decisions. The developed model not only acts as a tool to examine the short and long-term ecological and economic impacts of sea bass management policies but may also provide a platform to engage stakeholders, policy and scientists and facilitate shared system understanding. With acquisition and availability of more data, the model can be refined. In addition, there is scope to explore how the developed model framework can be adapted and implemented widely to inform policy decisions regarding other species and other geographical areas.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Data availability

The data underlying this article will be shared on reasonable required to the corresponding author.

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