REPORT

Edible Protein Energy Return on Investment Ratio (ep-EROI) for Spanish Seafood Products

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Abstract Life cycle assessment (LCA) has developed into a useful methodology to assess energy consumption of fishing fleets and their derived seafood products, as well as the associated environmental burdens. In this study, however, the life cycle inventory data is used to provide a dimensionless ratio between energy inputs and the energy provided by the fish: the edible protein energy return on investment (ep-EROI). The main objective was to perform a critical comparison of seafood products landed in Galicia (NW Spain) in terms of ep-EROI. The combination of energy return on investment (EROI) with LCA, the latter having standardized mechanisms regarding data acquisition and system boundary delimitation, allowed a reduction of uncertainties in EROI estimations. Results allow a deeper understanding of the energy efficiency in the Galician fishing sector, showing that small pelagic species present the highest ep-EROI values if captured using specific fishing techniques. Finally, results are expected to provide useful guidelines for policy support in the EU's Common Fisheries Policy.

Keywords Energy inputs · EROI · Fisheries · Food systems · Seafood

INTRODUCTION

Current fishing practices depend in many fisheries on large expenditures of energy, mainly fossil fuels. In fact, Tyedmers et al. (2005) have revealed that approximately 1.2 % of

world oil is used to fuel fishing fleets throughout the world. While fuel dependence implies an important economic limitation in most fisheries, it is also a matter of concern from an environmental perspective, due to the derived high greenhouse gas (GHG) emissions (Fredga and Mäler 2010).

These findings have recently fueled the debate around the environmental evaluation of fishing systems (Pelletier et al. 2007; Ford et al. 2012; Vázquez-Rowe et al. 2012a). In fact, until recent years environmental indicators in fisheries were limited to evaluating the stock of a particular species or group of species, focusing on the direct impacts of biomass removal from fisheries (Udo de Haes et al. 2002; Langlois 2012). However, the development of a series of environmental management tools in the past few years has increased the environmental aspects that are examined in these production systems, such as climate change, ozone depletion, eco-toxicity, or eutrophication (Pelletier et al. 2007).

An internationally standardized methodology, named life cycle assessment (LCA), has become one of the most common tools for assessing the environmental profile of fishing fleets (Pelletier et al. 2007; Vázquez-Rowe et al. 2012a; Avadí and Fréon 2013). This methodology evaluates the environmental burdens linked to a certain process, service or product from a life cycle perspective (ISO 2006). LCA computation is based on a thorough treatment of data inventory, as well as on a robust link to the final environmental impacts through the development of characterization factors, showing to be an optimal framework to monitor the energy requirements of products and services (Goedkoop et al. 2009). In fact, since the early 1990s, independent life cycle inventories (LCIs) and life cycle impact assessment (LCIA) methods have been constantly developed and updated thanks to an increasing interest in the methodology by industry and general providers (UNEP 2011).

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More specifically, life cycle management has developed standardized consistent rules and guidelines based on continuous transparency and accountability, harmonization of new approaches within the common framework or the existence of data exchange platforms (UNEP 2011). Therefore, in this study the use of life cycle thinking is proposed to nourish and improve the consistency of a commonly used assessment method for energy analysis: energy return on investment (EROI).

EROI is a term that flourished in the early 1970s and gained importance due to the fuel crisis in the 70s and 80s (Hall 1972; Gupta and Hall 2011). The most common use of EROI is within the energy sector in order to determine the energy that is returned from an energy-collecting process as compared to the energy that is required to provide this energy (Gupta and Hall 2011). In addition, broad comparisons of protein sources can be performed by calculating a dimensionless ratio of the edible protein energy content of an animal relative to the total industrial energy expended in its production/acquisition: the edible protein energy return on investment (ep-EROI) ratio (Tyedmers 2000; Hall 2011).

Pelletier et al. (2011) have highlighted the benefits of calculating EROI approaches to monitor energy return in food systems, since these rely on high inputs of non-renewable resources. More specifically, the use of ep-EROI in seafood products has shown to be highly relevant when examining the fishery stage, which in many cases may be highly energy intensive (Tyedmers 2001, 2004). In fact, ep-EROI provides a policy relevant approach to monitor the underlying energy sources used in fisheries in a way that markets cannot (Murphy and Hall 2010).

The coupling of these two methods (i.e., LCA and EROI) pursues a reduction in the uncertainties linked to the two main limitations of EROI: data quality and the fixation of the system boundaries (Murphy and Hall 2010). Additionally, the life cycle approach suggested allows a more robust comparison in terms of EROI between production systems as compared to more simplistic estimations such as fuel use intensity (FUI), since the latter does not consider the energy requirements of many fishery operations that rely on other

sources of energy (e.g., electricity, net, and ice production). Hence, the proposed methodology aims at providing not only an intra-assessment of fishing species between fisheries, but also an inter-assessment with other sources of protein (i.e., meat or aquaculture products) and food products in general (Tyedmers 2004; Pimentel et al. 2007; Pelletier 2008).

Consequently, the main aim of this study was to perform a critical comparison of a set of recently examined seafood products within the fishing fleet in Galicia (NW Spain) in terms of ep-EROI. The use of inventory data collected from LCA studies, as well as the estimation of cumulative energy demand (CED) through this life cycle perspective tool to calculate ep-EROI values is expected to strengthen the validity of results. More specifically, the partial objectives of the study were to (i) calculate the CED following LCA methodology of a set of 24 different fishing species captured with three different fishing techniques; (ii) determine the ep-EROI, based on life cycle thinking, linked to the extraction of the different species; and, (iii) perform a critical assessment of the similarities and differences between species and fishing techniques in terms of EROI to understand and rank their energy efficiency.

MATERIALS AND METHODS

Cumulative Energy Demand (CED) Calculation

The current research originated out of the interest in assessing the environmental profile of a set of fishing fleets in Galicia (NW Spain) using LCA. Hence, the available data were collected from a series of existing publications in the field of seafood LCA (Vázquez-Rowe et al. 2010a, 2011a, 2012b, c). A total of 98 vessels, representing a significant proportion of their specific fleets, were included in the present study, as can be observed in Table 1. Data acquisition is discussed in the [Supplementary Material](#) (SM). The ecoinvent® v2.2 Database was used for background processes (Frischknecht et al. 2007).

LCA and its life cycle perspective provide useful data and results for EROI calculation. A group of studies have

Table 1 Selected Galician fishing fleet samples for ep-EROI calculation

	F1	F2	F3	F4	F5	F6	F7
Sample size	30	24	9	12	9	5	9
Percentage over total (%)	18.2	23.8	14.3	20.7	33.33	6.4	24.3
Year of inventory	2008	2008	2008	2008	2009	2009	2000–2004
Total landings (tons)	12 597	16 056	3769	3416	5000	668	72 000
Total captures (tons)	12 998	27 750	6657	3473	6213	727	N/D

F1 coastal purse seining, *F2* coastal trawling, *F3* offshore trawling, *F4* offshore long lining (Northern Stock), *F5* trawling (Mauritania), *F6* offshore long lining Azores, *F7* tuna purse seining, *N/D* no data available

highlighted two important flaws when it comes to EROI estimation: setting the system boundaries to analyze the energy requirements of the assessed system and the fact that EROI is highly dependent on monetary data (Hall 2011). However, its combination with LCA, which has standardized mechanisms regarding data acquisition and system boundary delimitation, allows reducing these uncertainties.

In particular, one single impact category, CED, was selected from LCA for its combined use with ep-EROI (Fig. 1), in order to calculate the energy requirements of the selected production systems (VDI-Richtlinien 1997). SimaPro 7 was the software chosen for computing the results (Goedkoop et al. 2010).

The system under study in the LCA analysis included the different stages considered for fish extraction performed by the fishing fleets selected (Fig. 2). Hence, the products were followed from the production of the supply materials to the landing of fish at a Galician port, constituting what in LCA is named a “cradle to gate” perspective (Guinée et al. 2001). Further sections of the supply chain, such as processing or were disregarded due to the lack of data availability for all the supply chains.

While the use of LCA to calculate the total industrial energy expended in the extraction of fish products is considered highly precise, since it embraces not only the direct

expenditures, but also the background processes, LCA studies usually exclude human labor from the assessment (Nebel et al. 2006; Rugani et al. 2012). However, recent literature has started questioning this perspective, based on the assumption that human activities constitute an integral part of production systems, since part of these systems are sustained by human life (Rugani et al. 2012). However, given the lack of data, human labor activities, unlike in other EROI calculation approaches available in literature, were excluded from the present system.

The main function of the analysis is the estimation of the potential ep-EROI of the main fish species landed in Galician ports. The FU considered for each of the different marine species in the different fishing fleets was 1 ton of landed fish at port. Mass allocation was considered (Pelletier and Tyedmers 2011; Svanes et al. 2011). The rationale behind this decision, rather than assuming an economic allocation perspective, was based on the fact that the different fishing fleets evaluated operate in multispecies fisheries in which the catch of one species does not imply an increased strategic value over the rest of the landed species. Moreover, the use of alternative biophysical allocation approaches, such as energy density, was discarded due to the system boundaries delimited in this study, since they only consider the round weight landing of the fishing

Fig. 1 Graphical representation of the selected methodology

Fig. 2 Graphical representation of the system boundaries for the coupled LCA + EROI approach. *Note: gray rectangular boxes represent operational inputs of the fishing fleets assessed; dotted boxes represent operational inputs that are not common to all fishing fleets*

species at port without any on land processing. Hence, the calculations provided in this study assume that all the edible content of the analyzed systems will be used for human nutritional purposes.

Quantification of the Energy Output

The embodied energy was calculated based on the maximum edible content of the inventoried species and the protein content per 100 g of edible portion per FU. The specific values for each of the species were retrieved from a database developed and provided by the School of Resources and Environmental Studies (SRES) at Dalhousie University (Peter Tyedmers, personal communication). This database included the mean edible content and the protein content for 21 of the 25 marine species included in the assessment. Data for megrim and anglerfish, which were not available from this database, were retrieved from a national Spanish database (Xenotechs 2012). Moreover, data for forkbeard (*Phycis* spp.) and blackbelly rosefish (*Helicolenus dactylopterus*), two species that were landed by the offshore long lining fleet (NEAFC, ICES Divisions VIIIa, b, d and VII) were not included due to lack of available data regarding these two parameters. Finally, it should be noted that the energy content of protein was assumed to be 16.73 MJ/kg of protein (FAO 1985).

It should be noted that the system boundaries for the calculation of the output energy were fixed in the same terms as that of the CED calculation (Murphy and Hall 2010). Therefore, the assumption was made that all the edible protein energy content in the species assessed when landed at the fishing ports is finally delivered for human consumption, disregarding the potential food wastes that may occur in the on land supply chains (FAO 2011). Discards, which are discussed in more detail in the discussion, were excluded from the computation of the results as recommended by PAS2050-2:2012 (BSI 2012).

Edible Protein Content Energy Return on Investment (ep-EROI) Calculation

Finally, ep-EROI estimation was accomplished through calculating the coefficient between the protein energy output of the selected marine species and the energy inputs linked to fish extraction (CED impact category), following the formula (adapted from Tyedmers 2000; Hall et al. 2009):

$$\text{ep-EROI} = (\text{energy inputs/energy outputs}) \quad (1)$$

RESULTS

As abovementioned, a total of 23 different species, belonging to seven different industrial Galician fishing

fleets, were assessed in the current study, as can be observed in Table 2.

Coastal Fishing Species

A total of five different fishing species were assessed in the Galician coastal fishery. ep-EROI results ranged from 5.6 % in the case of European hake (trawling fleet) to 18.3 % for European pilchard (purse seining fleet). In fact, all species captured by purse seining vessels showed similar trends in their ep-EROI rate. Similarly, in the trawling fleet the collection of ep-EROI values was relatively small, ranging from 5.6 % (European hake) to 7.3 % (Atlantic mackerel). It is important to highlight the fact that two pelagic species, Atlantic mackerel and horse mackerel were captured indistinctively by the two fleets. Interestingly, direct comparison between fleets shows an 8.8 % decrease for horse mackerel and a 10.5 % reduction for Atlantic mackerel when these species are caught with trawl nets. Finally, the average ep-EROI for the evaluated coastal fishing fleets was 9.2 %.

Offshore Fishing Species

Four different offshore fleets were evaluated in the current study. While they are all linked to highly variable characteristics regarding the fishery or the fishing technique, ep-EROI values showed limited variance, ranging from 0.8 % (Norway lobster—Northern Stock trawling) to 2.8 % (Bigeye tuna—Azores long lining fishery). This led to an average ep-EROI of offshore fleets of 1.6 %. Nevertheless, despite the highly distinct characteristics of the assessed fishing fleets, a series of parallelisms were set.

In the first place, in the Northern stock the long lining fleet showed higher ep-EROI values than the trawling fleet. In fact, European hake, which was the only species that is captured and landed by both fleets, presented ep-EROI values 62 % higher for the long lining fleet. Secondly, if we compare the two long lining fleets, despite the fact that they target completely different species in different geographical areas, the range of values is relatively similar for all the species. Finally, if the two trawling fleets are compared, slightly higher EROI figures are observed for the Mauritanian fleet, which targets mainly cephalopods.

Open-Sea Fishing Species

Three different tuna purse seining fleets were included in this section. The ep-EROI values ranged from 8.9 % for the Pacific Ocean tuna captures and 12.9 % for tuna extracted in the Indian Ocean. The average value for the three pelagic fleets was 11.2 %. For this particular case study, the changes in ep-EROI were mainly linked to the CED of

each fishing fleet, since the caught species were in all three fleets the same.

Fishing Gear and Other Correlations

Fishing vessels relying on passive fishing gears were those that showed highest ep-EROI values regardless of the geographic location. Consequently, species captured by purse seiners showed in most cases values above 10 %, substantially higher than coastal trawlers, the following fleet in terms of ep-EROI. However, the other two trawling fleets presented the lowest return values. No apparent correlation was detected between the ep-EROI and the trophic level of the inventoried species.

Overall Galician Extractive Fishing Activity

Based on the ep-EROI values estimated for each of the different fishing fleets, the mean ep-EROI was calculated for the entire Galician extractive fishing sector (Fig. 3). Nevertheless, due to lack of available data, this approximation was calculated on the basis of industrial fishing fleets in the region and, therefore, excluding the still prominent small-scale fishing fleet. Thus, a total of 7053 TJ were invested by the industrial fishing fleet to perform their activities in the assessed period, with a return of the edible protein energy by the captured species of 535.9 TJ. Hence, the average estimate for the ep-EROI value for the Galician industrial fishing fleet was 7.6 %.

In an attempt to provide an average worldwide edible protein energy return, Tyedmers et al. (2005) calculated a mean value of 8.0 % for world fisheries. However, it must be noted that this estimation was based on the FUI of the assessed fishing fleets. Consequently, the estimate provided by Tyedmers et al. (2005) does not take into consideration the energy consumption linked to a set of background processes. Therefore, despite the worldwide estimate being 0.4 % higher than the approximation for the Galician fleet, the fact that non-fuel energy inputs are disregarded for worldwide fisheries would imply that a correction factor using life cycle standardized assumptions would lower this value considerably.

DISCUSSION

The Importance of EROI Estimation in Galician Fisheries

The analysis of ep-EROI of the assessed species constitutes, as far as we can ascertain, the first study of these characteristics performed for the Galician fishing fleet. In fact, the results allow a deeper understanding of the energy

Table 2 Edible protein energy return on investment (ep-EROI) values for the selected seafood products (CED, energy output and ep-EROI results are referred to the selected FU: 1 ton of landed fish)

Fishing fleet	Species	Scientific name	CED	Edible meat (%)	Protein content	Energy output (MJ) ^a	ep-EROI (%)
Coastal purse seiners (F1)	Horse mackerel	<i>Trachurus trachurus</i>	11 532	52	0.198	1722.5	14.9
	Atlantic mackerel	<i>Scomber scombrus</i>	11 532	61	0.201	2051.3	17.8
	European pilchard	<i>Sardina pilchardus</i>	11 532	62	0.203	2105.6	18.3
Coastal trawling (F2)	European hake	<i>Merluccius merluccius</i>	28 124	53	0.178	1578.3	5.6
	Horse mackerel	<i>Trachurus trachurus</i>	28 124	52	0.198	1722.5	6.1
	Atlantic mackerel	<i>Scomber scombrus</i>	28 124	61	0.201	2051.3	7.3
	Blue whiting	<i>Micro</i>	28 124	56	0.174	1630.2	5.8
Offshore trawling (F3)	European hake	<i>Merluccius merluccius</i>	117 656	53	0.178	1578.3	1.3
	Anglerfish	<i>Lophius budegassa</i>	117 656	50	0.149	1313.3	1.1
	Megrim	<i>Lepidorhombus spp.</i>	117 656	49	0.181	1483.8	1.3
	Norway lobster	<i>Nephrops norvegicus</i>	117 656	30	0.188	943.6	0.8
Offshore long lining (F4) ^b	European hake	<i>Merluccius merluccius</i>	73 471	53	0.178	1578.3	2.1
	Common ling	<i>Molva molva</i>	73 471	65	0.190	2066.2	2.8
	Conger eel	<i>Conger conger</i>	73 471	58	0.181	1756.3	2.4
	Atlantic pomfret	<i>Brama brama</i>	73 471	56	0.165	1545.9	2.1
Trawling—Mauritania (F5)	Common octopus	<i>Octopus vulgaris</i>	95 925	68	0.173	1968.1	2.1
	European squid	<i>Loligo vulgaris</i>	95 925	71	0.156	2006.4	2.1
	Common cuttlefish	<i>Sepia officinalis</i>	95 925	63	0.179	1886.6	2.0
	Common sole	<i>Solea solea</i>	95 925	49	0.181	1483.8	1.5
	Sand sole	<i>Pegusa lascaris</i>	95 925	60	0.182	1826.9	1.9
	Senegal hake	<i>Merluccius senegalensis</i>	95 925	53	0.163	1445.3	1.5
	Caramote prawn	<i>Penaeus kerathurus</i>	95 925	57	0.204	1954.9	2.0
Offshore long lining—Azores (F6)	Swordfish	<i>Xiphias gladius</i>	77 336	68	0.180	2047.8	2.6
	Porbeagle	<i>Lamna nasus</i>	77 336	51	0.199	1697.9	2.2
	Blue shark	<i>Prionace glauca</i>	77 336	51	0.174	1484.6	1.9
	Bigeye tuna	<i>Thunnus obesus</i>	77 336	57	0.231	2202.8	2.8
Open-sea tuna purse seining (F7) ^c	Skipjack/Yellowfin ^d	<i>Thunnus spp.</i>	19 225	62.5	0.238	2488.6	8.9
	Skipjack/Yellowfin ^e	<i>Thunnus spp.</i>	23 950	62.5	0.238	2488.6	10.4
	Skipjack/Yellowfin ^f	<i>Thunnus spp.</i>	28 085	62.5	0.238	2488.6	12.9

^a A generic value of 16.73 MJ per kg of protein was assumed for the energy content of protein (FAO 1985)

^b This fleet also lands significant amounts of forkbeard (*Phycis spp.*) and blackbelly rosefish (*Helicolenus dactylopterus*), but were excluded from the assessment due to lack of available data regarding edible content and protein content

^c A landing ratio of 50 % for skipjack and 50 % for yellowfin was assumed for the three fleets. Therefore, edible and protein content values represent medium values

^d Skipjack and yellowfin caught in the Atlantic Ocean

^e Skipjack and yellowfin caught in the Indian Ocean

^f Skipjack and yellowfin caught in the Pacific Ocean

efficiency in the Galician fishing sector, since the use of ep-EROI in combination with LCA provides a more comprehensive approach to the energy requirements of fishing systems than other commonly used indicators, such as FUI or other single issue indicators.

Unfortunately, the presented results represent the state-of-the-art during one year of fish extraction. Hence, the common finding that EROI values tend to decrease through

time—law of diminishing returns—could not be tested with this specific sample (Tyedmers 2001; Pracha and Volk 2011), but may be used in the future for such a purpose when new data are collected. Nevertheless, the results provide valuable information regarding energy requirements of the Galician industrial fishing fleets. In the first place, the revision of the Common Fishery Policy (CFP) by European authorities in 2013 has to be approached as an

Fig. 3 Average edible protein EROI values per fishing zone and average edible protein EROI for Galician industrial fishing fleets

opportunity not only to improve the EU's management of fishing stocks, but also as a chance to reduce the energy requirements of many fisheries through decision-making. In fact, this perspective would also offer a potential scenario for the reduction of the carbon footprint and other environmental impacts related to European fisheries (Vázquez-Rowe et al. 2011a, b). Secondly, an important milestone in the development of fishery ep-EROI studies is the fact that, unlike when these first arose in the 1970s, there has been an increasing perception by stakeholders regarding the importance of energy due to increasing fuel prices and more rigid fisheries management regulations. Finally, energy ratios such as EROI have provided important information regarding the imbalances between the increase in human populations and their thirst for energy, and the use of natural resources (Pimentel and Pimentel 2006). Therefore, the global perspective that is provided in this case study for a relevant European fleet will allow future study of time-dependent development of these fisheries in terms of energy investment.

However, the analysis of ep-EROI in this case study must also be performed at a global scale. According to a set of influential publications that have been published in the last 20 years, ecological economists forecast that the so-called "petroleum age" will end in the first few decades of the twenty-first century, although recent advances in technology and drilling may slightly

postpone this deadline (Meng and Bentley 2008; Almeida and Silva 2009). This situation will inevitably generate an increase in oil prices driven by a predicted increase in demand, in which the steady increase of renewable fuel production in some Western nations will not compensate the exponential increase in demand in emerging countries, as opposed to dwindling fossil fuel production (Day et al. 2009).

The predicted increase in fossil fuel prices in the following decades will most likely affect the economical sustainability of a traditionally heavily subsidized primary sector in Spain and Europe: fishing fleets (Pauly et al. 2003). Therefore, given that the highest energy expenditures in industrial fisheries are linked to direct energy inputs—75–90 % (Tyedmers 2004; Vázquez-Rowe et al. 2011b), it seems feasible to think that a change in the energy carrier for industrial fishing fleets will be needed in spite of predicted improvements in technology and energy efficiency (Destouni and Frank 2010). However, a recent study suggests that the use of alternative energy carriers (i.e., biofuels) for marine transportation would increase the primary energy use to fuel vessels, as well as a series of environmental impacts such as eutrophication or land use impact, despite the reduction in fossil fuel dependence and in climate change impacts (Bengtsson et al. 2012). Moreover, estimations concerning renewable energy production in the short- and mid-term do not indicate that the renewable mix may deliver

Fig. 4 Comparison of horse mackerel (*Trachurus trachurus*) captured by two coastal fishing techniques in Galicia (Source: Vázquez-Rowe et al. 2010a, b, 2012b)

current energy levels alone (Hirsch et al. 2005; Day et al. 2009).

Based on this reasoning, it seems plausible to predict a scenario in which those fisheries with lowest ep-EROI values will eventually encounter most difficulties to access competitive fuel prices to continue their activities. In fact, the low penetration of energy carrier modifications in the Galician fishing sector suggest that those fleets with lowest ep-EROI values will run into serious difficulties to maintain their competitiveness. More specifically, recent publications suggest that a major consequence of this future scenario may be the need to rely on small pelagic species for direct human consumption (Pauly et al. 2003), which, as can be seen in Table 2, show considerably higher ep-EROI values than any other fishery assessed if captured using specific fishing techniques. Having said this, it is important to mention that small pelagic species tend to show strong annual variations in stock abundance (Pauly et al. 1998; Fréon et al. 2008). Therefore, further fishing pressure on these stocks may increase their vulnerability (Allison et al. 2009).

Comparison Between the Assessed Fishing Fleets

As mentioned in “Fishing Gear and Other Correlations”, a high correlation was identified between the use of purse seining gears for seafood extraction and higher ep-EROI rates. While this fact is visible by direct comparison between the different fishing fleets, it gains more relevance when

horse mackerel and Atlantic mackerel, two species captured along the Galician coast, are examined in detail. These two species, captured in the same fishing areas by trawlers and purse seiners, not only show important ep-EROI improvements when captured by purse seiners, but this enhanced energy return, as observed in Fig. 4, is also accompanied by low potential environmental impact values (Vázquez-Rowe et al. 2010a), minor impacts in terms of seabed disturbance and lower discards, which also contribute to a reduced depletion of biotic resources (Vázquez-Rowe et al. 2012b).

Interestingly, a set of publications using the “LCA + DEA method” approach, which combines environmental LCA with data envelopment analysis (DEA), a linear programming method, suggest that fleets with increased energy demand have a higher operational efficiency and, therefore, less space for minimization of operational inputs and environmental impact reductions (Vázquez-Rowe et al. 2010b, 2011b).

Subsequently, these results exemplify the need for a redefinition of the CFP in terms of balancing the available natural resources with the most convenient fishing techniques in terms of fishing efficiency and environmental performance (Villasante and Sumaila 2010). Moreover, it should be noted that the lack of standardized social indicators in the sustainability assessment of fisheries is a current constraint in order to attain a comprehensive evaluation of fishing systems, since fishing can be an important source of employment in numerous coastal areas (Cocharne 2000; Iribarren and Vázquez-Rowe 2013).

Nevertheless, the on-going development of the social life cycle assessment (SLCA) may constitute a promising framework for future studies (Labuschagne and Brent 2006; Jørgensen et al. 2009; Dreyer et al. 2010).

Finally, similar results were also found for the hake fishery in the Northern Stock (Vázquez-Rowe et al. 2011a). However, in this particular case the considerable environmental gains of fishing hake with long lining techniques rather than trawlers was not complemented with an important difference in energy return (Table 2).

At this stage it is important to highlight the fact that life cycle perspective studies carried out traditionally account for an attributional perspective, that is, view production systems as steady-state systems. However, in the last decade consequential life cycle assessment (C-LCA) has developed as a more comprehensive approach in which the consequences of a variation that affect the initial system are analyzed (Schmidt and Weidema 2008). In fact, in many cases the predicted future change scenarios are computed through a selection of economic models (Dandres et al. 2012). While this particular study has only

assessed the energy inputs of industrial fleets from an attributional perspective, the analysis would gain in comprehensiveness if C-LCA were implemented, in order to detect the marginal consequences of fisheries management decisions. Moreover, the validity of a C-LCA approach is also extendable to the computation of EROI, provided that the production system follows a life cycle inventory perspective, in order to determine the energy returns related to *shocks* in the structure of these systems.

Contextualization of the Results and Comparison with Other Sources of Protein

The use of ep-EROI to assess the energy expended in the acquisition of seafood has been developed in many other fisheries. Table 3 provides a small summary of available ep-EROI values in literature. For instance, it should be noted that the ep-EROI values for the purse seining fleets included in this study are substantially lower than most of those collected in literature (Tyedmers 2001). Nevertheless, many of these fisheries are linked to landings that are destined for

Table 3 ep-EROI values for other fishing, aquaculture and agriculture food products

Fishing				
Species	Country	Fishing gear	Year	EROI (%)
Menhaden	United States	Purse seining	1999	167 ^a
Atlantic mackerel	Basque Country (Spain)	Purse seining	2001–2008	68.6 ^b
Tuna	Global	Purse seining	2009	14.0 ^c
Patagonian grenadier	Galician fleet in Chile	Trawling	2010	10.4 ^d
Global fisheries	–	Varied	–	8.0 ^e
Tuna	Global	Long lining	2009	5.9 ^c
Shrimp	Canada	Trawling	1999	4.1 ^a
Swordfish	Canada	Long lining	1999	3.4 ^a
Aquaculture				
Species	Country	Type	Year	EROI (%)
Mussels	Scandinavia	Extensive	N/Sp	10–15 ^a
Mussels	Spain	Extensive	2007	6.9 ^f
Shrimp	Thailand	Intensive	N/Sp	1.4 ^g
Livestock				
Species	Country		Year	EROI (%)
Chicken	United States		N/Sp	25 ^h
Swine	United States		N/Sp	7.1 ^h
Swine	Spain		2011	3.8 ⁱ
Beef cattle	United States		N/Sp	2.5 ^h
Milk	Spain		2002	7.2 ^j
Lamb	United States		N/Sp	1.8 ^h

^a Tyedmers (2001), ^b Ramos et al. (2011), ^c Parker and Tyedmers (2012), ^d Vázquez-Rowe et al. (2013), ^e Tyedmers et al. (2005), ^f Iribarren et al. (2010), ^g Troell et al. (2004), ^h Pimentel and Pimentel (2003), ⁱ Unpublished, ^j Hospido et al. (2003)

fishmeal production, rather than direct human feeding, the latter being the case in the Galician fleets assessed.

Galician offshore trawling and long lining fisheries, as far as we could ascertain through a comprehensive set of publications, constituted the fleets with lowest ep-EROI values, which highly questions the efficiency of these fleets in terms of energy return. This situation highlights the vulnerability of these fleets in a predicted energy-scarce future (Day et al. 2009).

Finally, large-pelagic species caught by large Galician purse seiners around the world show similar ep-EROI values to the average for global tuna purse seining fisheries. Moreover, the ep-EROI of tuna species captured with purse seiners is substantially higher than those landed with long lining or pole and line gears (Parker and Tyedmers 2012). However, no specific data were available in this case study for the Galician pole and line tuna fishery.

When the computed values in this study are compared to other sources of protein, it is important to highlight that only swine and milk were available sources of protein produced in Galicia, which limits the comparability of the products (see Table 3). Nevertheless, literature data suggest that livestock products, such as lamb or beef, and intensive aquaculture products, have similar ep-EROI levels to fish species caught with trawling and long lining techniques, while extensive aquaculture products (e.g., mussels) or poultry showed ranges comparable to pelagic species captured with purse seiners.

Methodological Choices Affecting EROI Calculations

Despite the utility of EROI when it comes to comparability between fleets from an energetic perspective, the methodology assumptions that are taken into account can cause a set of uncertainties that must be considered and discussed. In the first place, all ep-EROI estimates must be seen as overestimates, since the current study only computed the extraction

phase of seafood supply chains. Hence, the decrease in ep-EROI when considering the entire supply chain up to consumption will depend on a set of multiple factors, such as the level of processing, storage conditions, transportation or the food waste that is generated throughout the supply chain. The lack of data availability and the complexity of on land seafood supply chains impeded the expansion of the system boundaries of the assessment to these stages, such as processing, retailing, or consumption. Nevertheless, in Fig. 5 a small number of different production systems have been followed to the consumption stage. The results show an important decrease in the ep-EROI for those products with medium values (5–10 %), while those with low ep-EROI values show limited reductions due to the high overall contributions of the fishing activities. In fact, all seafood products arriving from industrial fishing fleets available in literature have reported the highest energy inputs taking place in the fishing phase (Vázquez-Rowe et al. 2011b; Ziegler et al. 2011).

Secondly, allocation constitutes an important source of result variations in life cycle studies in multispecies fisheries. For instance, as observed in Table 4, the variation in EROI results with respect to mass allocation when an economic allocation approach is taken into consideration

Table 4 Changes in final ep-EROI results using economic allocation

Fishing species	Fishing gear	ep-EROI (%)		Difference (%)
		Mass allocation	Economic allocation	
European pilchard	Purse seining	18.3	18.3	−0.1
European hake	Trawling (offshore)	1.3	1.7	+30.8
Anglerfish	Trawling (offshore)	1.1	0.9	−18.2
Common octopus	Trawling	2.1	2.1	+0.3

Fig. 5 ep-EROI of selected species throughout their supply chain. Data sources: Vázquez-Rowe et al. (2013), Iribarren et al. (2010)

Table 5 Sensitivity analysis for selected species based on the upper and lower standard deviation values of life cycle inventory items

Fishing species	Fishing fleet	ep-EROI (%)	ep-EROI (%) worst scenario	ep-EROI (%) best scenario
Horse mackerel	F1	14.9	10.7	24.5
Pilchard	F1	18.3	13.1	30.0
Atlantic mackerel	F1	17.8	12.8	29.2
European hake	F2	5.6	4.7	7.0
Atlantic mackerel	F2	7.3	6.1	9.1
Horse mackerel	F2	6.1	5.1	7.6
Blue whiting	F2	5.8	4.8	7.2

The standard deviation of the life cycle inventory of the two selected fishing fleets was based on a sample of 30 fishing vessels for F1 and 24 vessels for F2

The worst scenario of ep-EROI computation considers the upper standard deviation values for operational inputs in the life cycle inventory

The best scenario of ep-EROI computation considers the lower standard deviation values for operational inputs in the life cycle inventory

F1 coastal purse seiners, *F2* coastal trawlers

will vary depending on the differing prices of the landed species. Nevertheless, it should be highlighted that changes in the allocation approach will not change the global EROI results for a single production unit (i.e., fishing vessel or fishing fleet).

A third source of uncertainty that was identified was the high standard deviations in terms of operational inputs observed between individual fishing vessels in some of the fleets assessed. Hence, as can be seen in Table 5, the range of ep-EROI values for species caught by coastal purse seiners can show ranges of up to 250 % from the best to the worst performing scenario, whereas the range for coastal trawlers was identified as substantially smaller. Having said this, it should be noted that other sources of uncertainty, linked to process energy requirements or illegal and unreported fishing by vessels may also be important sources of uncertainty in reporting ep-EROI values for these fisheries.

Finally, in terms of the system boundaries of the fishing phase, as shown in Fig. 1, unutilized captured species (i.e., discards) were not accounted for. On the one hand, this constitutes a logical perspective from an output perspective, since discards return, in many cases dead, to the ocean, so their computation in terms of energy as an output of the system would be deceiving. On the other hand, the large amounts of discards that are produced in fisheries have been confirmed in previous studies for the inventoried fishing fleets (Vázquez-Rowe et al. 2011c, 2012b). In fact, Vázquez-Rowe et al. (2011c) estimated 60 255 tons of discards in the Galician fishing sector in 2008, representing 17 % of the total capture, which could translate into approximately 120 TJ of wasted embodied energy. Moreover, it is important to note that many of the species that Galician fishermen reported discarding, such as horse mackerel, are those with higher levels of embodied energy (Vázquez-Rowe et al. 2012b). Consequently, a future improvement in ep-EROI computation may consider the

loss of discards and other food wastes throughout the supply chain as a source of inefficiency when calculating the embodied energy of the fish yield, therefore lowering the ep-EROI values of operations with discards. Similarly, this perspective could also be applied in those fleets that use bait for extractive operations.

CONCLUSIONS AND PERSPECTIVES

Increasing seafood demand due to human population growth constitutes a main risk in terms of guaranteeing the sustainability of fish stocks. Moreover, current energy consumption patterns will have to be reduced on a mid-term basis, due to depleting fossil fuel resources. Therefore, industrial fishing fleets which are strongly dependent on these two dwindling natural resources are bound to suffer an important reconversion in decades to come.

The use of ep-EROI arises as a useful indicator to monitor the fragile balance between edible energy that humans obtain from the oceans and the energy needed to power the fishing activities. The current study presented a wide range of ep-EROI values for the most representative fishing species captured by industrial fishing vessels in Galicia. While these results constitute the first of its kind for this specific case study, they are intended to provide useful information for the future management of these fisheries. Additionally, the life cycle perspective given to EROI calculation, through the use of LCA inventories, confers a solid and standardized methodology background to the study, allowing the reproducibility and comparability of the results. Finally, it also permits parallel computation of potential environmental impacts, which adds an environmental sustainability dimension to the evaluation of EROI.

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