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## **Novel approach for testing the food limitation hypothesis in estuarine and coastal fish nurseries**

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### **Abstract :**

Survival success of early life stages of fish is regulated by density-dependent effects, but the limiting factors explaining these effects have not been well identified. In coastal habitats, juveniles of many fish species occur in high concentrations and possibly compete for food resources. This study compared the ratio of food consumption to benthic prey production to test whether food availability is a major factor defining the carrying capacity of fish nurseries. We developed a method to quantify the exploitation efficiency (also called ecotrophic efficiency) of the juvenile fish feeding on benthic prey, expressed as a ratio of food consumption to food production. This method includes many sources of uncertainty and a key parameter of prey accessibility. Applied to the case study of the Bay of Vilaine (north Bay of Biscay), results suggest food limitation for juvenile fish. The generic nature of this method supports its wide application in various nursery habitats. As food limitation is a density-dependent process having a dampening effect on recruitment variability, examining its occurrence over time and space will improve our comprehension of nursery-dependent fish dynamics.

**Keywords :** Exploitation efficiency, Predator-prey relationship, Food consumption, Fish juvenile, Nursery habitat, Bioenergetics, Density dependence, Carrying capacity, Secondary production

## 1. INTRODUCTION

Estuarine and coastal habitats are suitable nurseries for a large proportion of demersal and benthic fish species (Seitz et al. 2014, Brown et al. 2018) and are thus considered essential for completing their life cycle (Peterson et al. 2000, Beck et al. 2001, Fulford et al. 2011). Coastal nursery dependent species congregate at the juvenile stage in these spatially restricted habitats that supply abundant food resources and act as a potential refuge from predators (Gibson 1994, Gibson et al. 2002). This fish concentration is suspected to result in density-dependent processes, limiting the growth (Bacheler et al. 2012), survival, and thus recruitment of fish populations (Iles & Beverton 2000, Minto et al. 2008). The positive relationship between surface areas of nursery habitats and the resulting average recruitment (Rijnsdorp et al. 1992, Kostecki et al. 2010, Wetz et al. 2011) supports this hypothesis. However, demonstration of density dependence does not indicate the cause of the limitation (Sinclair & Pech 1996). Even though some critical environment conditions can severely impact the carrying capacity of nursery habitats (e.g. van der Veer et al. 2000), the underlying processes remain poorly understood. Competition for food is assumed to be a key process (i.e. Gibson 1994), but the causal link between density-dependent survival and food is still debated (Le Pape & Bonhommeau 2015). Some studies suggest that benthic invertebrate populations are only minimally impacted by their predators (e.g. Gee et al. 1985, Shaw & Jenkins 1992); consequently, survival of juvenile fish would not be dependent on food availability (Ross 2003, Hampel et al. 2005, Vinagre & Cabral 2008). However, other studies propose that the distribution of benthic invertebrates can be regulated by their predators in estuarine and coastal ecosystems. Food availability would then be a factor limiting the survival of juvenile fish in nursery habitats (Nash & Geffen 2000, Nash et al. 2007, Craig et al. 2007): this is the food limitation hypothesis (Le Pape & Bonhommeau 2015).

Two approaches are commonly used to test whether food is limiting in coastal areas. The indirect approach focuses on growth variations. It assumes that the *in situ* growth rate would decrease with the density of juveniles if they compete for food (e.g. van der Veer & Witte 1993, Craig et al. 2007). However, this approach could lead to the erroneous rejection of the hypothesis of food limitation. Indeed, even in a food limitation context, the apparent growth of a juvenile fish population could remain maximal because of the highly size-selective mortality of juvenile fish: larger individuals have a higher survival than smaller ones (Sogard 1997, Levin et al. 1997, Le Pape & Bonhommeau 2015). Alternatively, the direct approach quantifies the exploitation pressure applied by consumers on their prey. Exploitation efficiency (EE; also called ecotrophic efficiency) is the ratio of food consumed by the juvenile fish community to the food supply represented by the production of the benthic invertebrate community (Collie 1987, Vinagre & Cabral 2008). This ratio is an intermediate component to compute ecological efficiency, which quantifies energy transfer among trophic levels (Lindeman 1942). It directly quantifies the portion of benthic production consumed by their predators; thus, it is an indicator of predation pressure. In this context, the food limitation hypothesis would be accepted if EE is high over years and/or over nursery habitats.

Few studies have carried out the direct approach to assess the predation pressure applied by one ecological guild on another. This method requires collecting a large amount of quantitative data on many marine species, including both the marine juvenile fish community and their benthic prey. Generally, one of the 2 following methods are used to estimate food consumption (FC). First, the gut-content method, which is a flux analysis requiring time-consuming experimental work. Gut contents must be weighed at constant intervals to determine the evacuation rate of each fish species (Elliott & Persson 1978). This method likely underestimates FC, as regurgitation often occurs soon after fish capture (e.g. Elliott & Hemingway 2002, Vignon & Dierking 2011). The second approach is based on bioenergetics and estimates FC from fish growth. The energy conversion process can be more or less exhaustive; e.g. ranging from a very detailed approach using bioenergetics models (e.g. dynamic energy budget [DEB] theory; Kooijman 2009) to a largely simplified one, using mass-balanced trophic models (e.g. the Ecopath framework; Christensen et al. 2005). Assessing the quantity of food that is ingested to obtain annual fish production requires a compromise between (1) an exhaustive description of the processes involved in the conversion of ingested food into fish biomass and (2) the availability of reliable data to describe this conversion process. This compromise precludes the systematic use of bioenergetics models. DEB models have been used successfully to estimate juvenile food limitation for a well-studied coastal nursery dependent species (van der Veer et al. 2010, 2016). However, the DEB approach requires data and knowledge on a variety of fine metabolic processes that are mostly undescribed

for marine juvenile fish, preventing its use in a multispecific approach. Mass-balanced trophic models are used to estimate flows between functional groups in an ecosystem (Christensen et al. 2005). These models, also based on bioenergetics, estimate the total EE of prey. However, mass-balanced models use an oversimplified description of growth and are not well suited to analyze short-term processes (i.e. turnover rate of prey production in coastal and estuarine systems; Ritter et al. 2005). Hence, these 2 families of models are not designed to focus on the food limitation hypothesis in estuarine and coastal fish nurseries. Therefore, we need a method that is based on bioenergetics, but less complex than a full DEB calculation.

The few studies that focus on predation of benthivorous fish generally estimate a low EE of the benthic prey, indexing low predation pressure (e.g. Vinagre & Cabral 2008). However, they do not necessarily conclude that there is an absence of food limitation (Collie 1987). Indeed, benthic production is shared by many fish species in coastal nursery habitats (McLusky & Elliott 2004, Nicolas et al. 2010). By considering only a few consumer species, most studies assess only a small part of the total EE of prey production. This key point underlines the need to account for a representative part of the consumers relying on the same pool of prey in order to fully evaluate the food limitation hypothesis.

The limits of the existing approaches to assess fish consumption emphasize the need to develop a bioenergetics-based approach responding to the constraints induced by data availability, but also sufficiently precise to quantify predation pressure and thus deal with the food limitation hypothesis in multispecies fish nurseries. In this paper, we developed a method to quantify energy flow between 2 compartments: the benthic invertebrate community and the benthivorous juvenile fish community. This methodology aims to estimate the ratio of FC of juvenile fish to benthic food production (FP) by quantifying 2 key intermediate components: fish production and prey production (Fig. 1). This approach accounts for prey accessibility and quantifies the uncertainty associated with input parameters. We applied this methodology to the Bay of Vilaine nursery ground (Bay of Biscay, Western Europe) to test the food limitation hypothesis.

## **2. MATERIALS AND METHODS**

### **2.1. Computing EE**

Our objective was to quantify energy flow between benthic macroinvertebrates and benthivorous fish living in estuarine and coastal nursery ecosystems, a community mostly dominated by juvenile fish (Gibson 1994). We estimated EE, which is the ratio of juvenile fish FC to benthic FP. EE is a baseline for the analysis of the food limitation hypothesis in fish nursery habitats (Fig. 1).

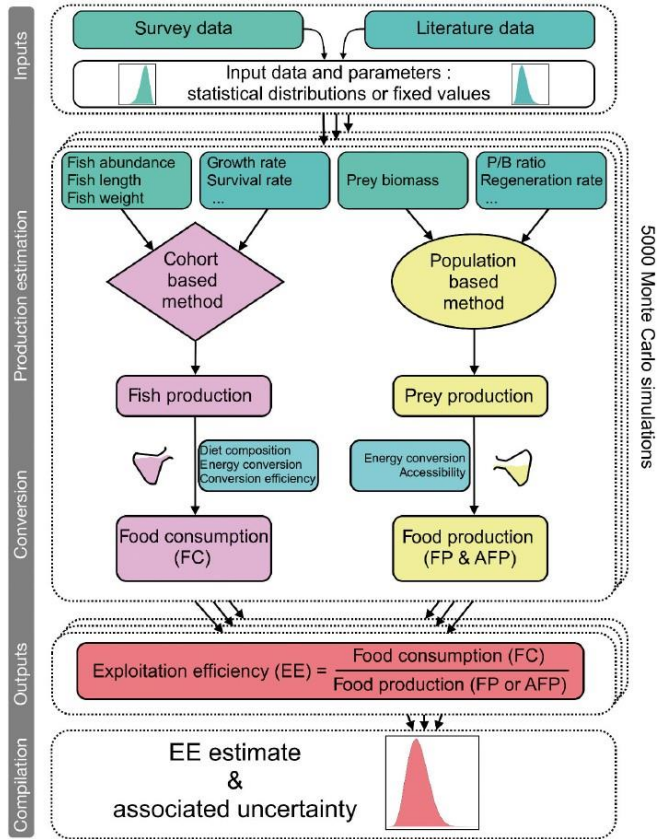


Fig. 1. Computational flowchart used to estimate exploitation efficiency (EE), including uncertainty analysis with Monte Carlo sampling. AFP: accessible food production

## 2.2. FC

The FC metric estimates the quantity of food consumed annually by a community of consumers. The bioenergetics approach computes fish production to then determine the FC of juvenile fish. For a single individual, annual production refers to its growth over 1 yr. Extrapolation to the population level is carried out either by integrating over time the product between instantaneous fish number and instantaneous growth rate, or by using its production-to-biomass ratio, which integrates both. Unlike macrobenthic invertebrates, a large proportion of fish species are not resident in coastal shallow water habitats, as they migrate to deeper waters as adults (Seitz et al. 2014). In this context, the production-to-biomass ratio, referring mostly to an entire population in the literature, is not appropriate to estimate juvenile fish production within nursery habitats. Moreover, as fish feed on benthic macroinvertebrates for only a limited period of the juvenile stage, the time window must be properly delimited. Both arguments lead to estimate FC from mortality and growth rates. Data collection is detailed in Supplement S2 at [www.int-res.com/articles/suppl/m629\\_p117\\_supp.pdf](http://www.int-res.com/articles/suppl/m629_p117_supp.pdf).

The biomass production ( $P$ , in  $\text{weight yr}^{-1}$  or  $\text{weight surface}^{-1} \text{yr}^{-1}$ ) of a juvenile cohort during the growth period is estimated as:

$$P = \int_{t=t_0}^{t=T} n(t) \cdot \frac{dw}{dt} \cdot dt \quad (1)$$

where  $t_0$  and  $T$ , respectively, refer to the beginning and end of the growth period when juvenile fish feed on benthic macroinvertebrates and water temperature is correspondingly higher;  $n(t)$  is the number of individuals at time  $t$ ; and  $\frac{dw}{dt}$  is the instantaneous growth rate. As the integration in Eq. (1) is not straightforward, it is discretized through a daily basis in Eq. (2) to estimate  $P$  of a juvenile cohort (in  $\text{weight yr}^{-1}$ , or in  $\text{weight surface}^{-1} \text{yr}^{-1}$ ):

$$P = \sum_{d \in d_0:D} n_d \cdot (w_d - w_{d-1}) \quad (2)$$

where  $d_0$  and  $D$ , respectively, are the first and last day of the growth period;  $n_d$  is the number of individuals in the middle of day  $d$ ; and  $w_d$  and  $w_{d-1}$  are the individual weights at the end of day  $d$  and day  $d-1$ . The difference

between the 2 weights provides the individual production for day d. The 2 components of Eq. (2) ( $n_d$  and  $w_d$ ) can be computed using survey data, daily growth rate, and daily mortality rate.  $n_d$  is estimated as:

$$n_d = \frac{c_s}{q} \cdot e^{-(d-s)Z} \quad (2.1)$$

where s is an index of the survey date;  $c_s$  is fish abundance in number or number surface<sup>-1</sup>; q is catch efficiency; and z is daily mortality (in d<sup>-1</sup>).  $w_d$  is estimated as:

$$w_d = a \cdot [L_s + (d + 1/2 - s) \cdot G]^b \quad (2.2)$$

where G is the daily growth rate of the studied species observed in the literature (Supplement S2);  $L_s$  is the average fish length of a single cohort observed in the survey at day s; and a and b are parameters of the length-weight relationship.  $d_0$  (Eq. 2.3) is the day when an individual fish reaches the minimum size to actually feed on macrofauna:

$$d_0 = \frac{L_{d_0} - L_s}{G} + s \quad (2.3)$$

where G (defined above) is assumed to be constant during the main growth period;  $L_s$  is as defined above; and  $L_{d_0}$  is the average fish length corresponding to a diet shift towards macroinvertebrates, defined from gut content analyses (Tableau et al. 2015). P can then be expressed from Eqs. (2), (2.1), (2.2), and (2.3) as follows:

$$P = \frac{c_s}{q} \cdot e^{sZ} \cdot a \cdot \sum_{d \in d_0:D} e^{-dZ} [(L_s + (d + 1/2 - s) \cdot G)^b - (L_s + (d - 1/2 - s) \cdot G)^b] \quad (3)$$

where D, the end of the main growth period, occurs in late fall in temperate ecosystems (Hamerlynck & Hostens 1993). FC is then derived from P. As the bioenergetics approach refers to energy units, P must be converted into energy production. To do so, we used data on gross conversion efficiency (K) (Hidalgo et al. 1987), defined as the quantity of ingested energy required to produce one energy unit of juvenile fish. As macroinvertebrates may represent only a part of the diet of some roundfish species (Hamerlynck & Hostens 1993), only that part of the production must be considered. Therefore FC of the benthivorous fish community, expressed in energy yr<sup>-1</sup> or energy surface<sup>-1</sup> yr<sup>-1</sup>, is calculated as:

$$FC = \sum_{i \in 1:1^{th} \text{ fish cohort}} P_i \cdot DC_i \cdot E_i \cdot \frac{1}{K_i} \quad (4)$$

where  $P_i$  is the biomass production of fish cohort i;  $DC_i$  is the proportion of benthic macroinvertebrates in the diet estimated using stomach contents; and  $E_i$  is the energy density gathered from the literature (Supplement S2).

### 2.3. Benthic FP

Benthic invertebrate species were considered potential prey if they have been observed in juvenile fish gut contents (determined from literature studies on juvenile diet or from our own observations; see details in Tableau et al. 2015 and Supplement S2). Since benthivorous juvenile fish are considered to be opportunistic feeders (De Vlas 1979, Hampel et al. 2005, van der Veer et al. 2011, Schücker et al. 2012), FC cannot be partitioned among prey species. For consistency, the biological productions of all macrobenthic prey species are summed to estimate FP. As the mobility of benthic invertebrate prey is limited, one can assume that they remain in the coastal nursery all their lives. Thus, production-to-biomass ratio data referring to entire populations can be used to compute their production (Brey 2001). The 'available benthic energy coefficient' (ABEC) was developed for this purpose (Tableau et al. 2015). The Brey Model was used because it the most accurate model, especially for marine assemblages (Brey 2012). Since the benefits of a correction coefficient suggested in Brey (2012) remain an open question, we chose not to use it. As ABEC is only applicable to average annual biomasses, biomasses observed during the survey were corrected. The resulting biomass production was converted into energy by a species-specific coefficient, since energy density varies widely among in vertebrate species. For instance, energy density is 1.02 kJ g<sup>-1</sup> for the bivalve *Corbula gibba*, whereas it is 5.84 kJ g<sup>-1</sup> for the polychaete *Lumbrineris* sp. and 8.19 kJ g<sup>-1</sup> for *Ampelisca* sp. (Brey et al. 2010). FP is expressed in energy yr<sup>-1</sup> or energy surface<sup>-1</sup> yr<sup>-1</sup> as follows:

$$FP = \sum_{j \in 1:j^{\text{th}} \text{ prey species}} CR \cdot B_j \cdot P : B_j \cdot (1 + R_j) \cdot E_j = \sum_{j \in 1:j^{\text{th}} \text{ prey species}} CR \cdot B_j \cdot ABEC_j \quad (5)$$

where CR is a ratio converting the biomass observed during a survey at a given period of the year into average annual biomass (Tableau et al. 2015);  $B_j$  is the biomass observed during a survey (in weight or weight surface<sup>-1</sup>);  $P : B_j$  the production-to-biomass ratio estimated from an empirical model accounting for water temperature, but which does not account for regeneration after sublethal fish cropping (Brey 2012) (in yr<sup>-1</sup>);  $R_j$  is a regeneration coefficient (Tableau et al. 2015) accounting for somatic regeneration (i.e. production-to-biomass must be raised by 15% for *Amphiura filiformis* to account for regeneration; Skold et al. 1994); and  $E_j$  is the energy density (in energy weight<sup>-1</sup>) for the  $j^{\text{th}}$  prey species.

Only accessible prey matters for a predator (Tableau et al. 2015, van der Veer et al. 2016). ABEC (Tableau et al. 2015) allows us to weight the FP of a species by an accessibility coefficient based on observed juvenile fish prey catch rates. According to Tableau et al. (2015), 2 accessibility categories can be statistically identified; the authors suggested setting 1 as the coefficient of easily accessible prey and 0.11 as the coefficient of hardly accessible prey. When included in the FP equation (Eq. 5), the accessibility coefficient ( $A_j$ ) gives the accessible FP (AFP):

$$AFP = \sum_{j \in 1:j^{\text{th}} \text{ prey species}} CR \cdot B_j \cdot P : B_j \cdot (1 + R_j) \cdot E_j \cdot A_j \quad (6)$$

## 2.4. Partial uncertainty analyses

The computation of EE requires a large amount of data and parameters, usually at the species level (Table 1). Since quality of information can be poor on some parameters and data, uncertainty analyses were carried out. To do so, we classified the data and parameters following their quality in 3 categories, each of which were treated differently (Table 1).

- 1<sup>st</sup> category: data and parameters with negligible uncertainty. Information comes from the studied species. Values are defined as fixed values. Typically, fish length can be considered in this category.
- 2<sup>nd</sup> category: data and parameters with highly quantified uncertainty. Information comes from the studied species but is uncertain given observation error (e.g. data on density), given the region and/or life stage at which the information is gathered, or because it is inferred from species taxonomically and functionally close to those observed in the data set (e.g. parameters on mortality rate). For this category, uncertainty is considered as known and/or estimated from the different sources of information. Each data point or parameter is defined using a statistical distribution (see Table 1 and Supplement S1 for details on the distributions).
- 3<sup>rd</sup> category: data and parameters with highly unquantified uncertainty. Unlike the 2<sup>nd</sup> category, there is a lack of knowledge and references to inform the values of this category. A conservative approach is needed. It consists of selecting, in a large range of uncertainty, the value of the data or parameter leading to a minimal EE. When at least one parameter is defined in that category, only a minimum threshold estimate of the EE is estimated. EE was computed using the Monte Carlo method (Metropolis & Ulam 1949). Random sampling in parameter distributions were repeated 5000 times to build the final distributions (Fig. 1).

Table 1. Categorization for the data and parameters. A resolution at the species level (yes, Y) associated with negligible uncertainty (Y) leads to the use of fixed values. When data and parameters are not defined at the species level (no, N) and/or have high uncertainty (N), there are 2 possibilities: if several sources are available (Y), values are defined with an associated distribution; if the uncertainty is unknown (N), a conservative approach is used. N\*: data are unavailable for some fish cohorts, but the latter are still informed using data from other fish species. /: not applicable

| Parameter                                     | Description                 | Sources of information                | Information at species level | Negligible uncertainty | Known uncertainty | Category of uncertainty | Statistical distribution |
|---|-----------------------------|---------------------------------------|------------------------------|------------------------|-------------------|-------------------------|--------------------------|
| <b>Food consumption in energy (fish data)</b> |                             |                                       |                              |                        |                   |                         |                          |
| C <sub>s</sub>                                | Fish abundance              | } Surveys                             | Y                            | N                      | Y                 | 2-distribution          | Gamma                    |
| s   | Survey date index           |                                       | Y                            | Y                      | /                 | 1-fixed data            | /                        |
| L <sub>s</sub>                                | Fish length                 | } Deduced from surveys                | Y                            | Y                      | /                 | 1-fixed data            | /                        |
| a   | Length-weight parameter     |                                       | Y                            | Y                      | /                 | 1-fixed data            | /                        |
| b   | Length-weight parameter     |                                       | Y                            | Y                      | /                 | 1-fixed data            | /                        |
| L <sub>d0</sub>                               | Diet shift length           |                                       | Y                            | Y                      | /                 | 1-fixed data            | /                        |
| d <sub>0</sub>                                | Diet shift date index       | } Deduced from surveys and literature | N*                           | N                      | N                 | 3-conservative          | /                        |
| D   | Growth end index            |                                       | N                            | N                      | N                 | 3-conservative          | /                        |
| q   | Catch efficiency            | } Literature                          | N*                           | N                      | N                 | 3-conservative          | /                        |
| Z   | Mortality rate              |                                       | N*                           | N                      | N                 | 3-conservative          | /                        |
| G   | Growth rate                 |                                       | N*                           | N                      | N                 | 3-conservative          | /                        |
| DC  | Diet composition            |                                       | Y                            | N                      | N                 | 3-conservative          | /                        |
| E   | Energy density              |                                       | N                            | N                      | Y                 | 2-distribution          | Gamma                    |
| K   | Gross efficiency            |                                       | N                            | N                      | Y                 | 2-distribution          | Inverse gamma            |
| <b>Food production in energy (prey data)</b>  |                             |                                       |                              |                        |                   |                         |                          |
| B   | Invertebrate biomass        | Surveys                               | Y                            | N                      | Y                 | 2-distribution          | Gamma                    |
| CR  | Conversion ratio            | } Deduced from surveys                | N                            | N                      | Y                 | 2-distribution          | Beta                     |
| A   | Accessibility               |                                       | N                            | N                      | Y                 | 2-distribution          | Beta                     |
| P:B   | Production-to-biomass ratio | } Literature                          | Y                            | N                      | Y                 | 2-distribution          | Lognormal                |
| R   | Regeneration rate           |                                       | N                            | N                      | N                 | 3-conservative          | /                        |
| E   | Energy density              |                                       | Y                            | Y                      | /                 | 1-fixed data            | /                        |

## 2.5. Application to a temperate nursery habitat: the Bay of Vilaine, France

### 2.5.1. Study site

The Bay of Vilaine is a soft-bottom habitat under estuarine influence that is used as a nursery by several benthic and demersal fish species of commercial interest (Le Pape et al. 2003). It has been studied for more than 30 yr, with valuable knowledge gained regarding its fish (Nicolas et al. 2007, Kopp et al. 2013) and benthic invertebrate communities (Le Bris & Glemarec 1995, Brind'Amour et al. 2014). Given such data and knowledge-rich context, the bay constitutes a relevant framework in which to analyze predator-prey relationships (Le Pape et al. 2003, Kostecki et al. 2010, Tableau et al. 2016). The studied area covers the subtidal zone located from 5 to 30 m depth and consists mostly of sandy mud sediments (Le Bris & Glemarec 1995). It was stratified into 3 zones along the bathymetric gradient (see Supplement S2 for details). All samples were collected exclusively on this type of sediment, explaining the shape of the geographic domain of the study (Fig. 2).



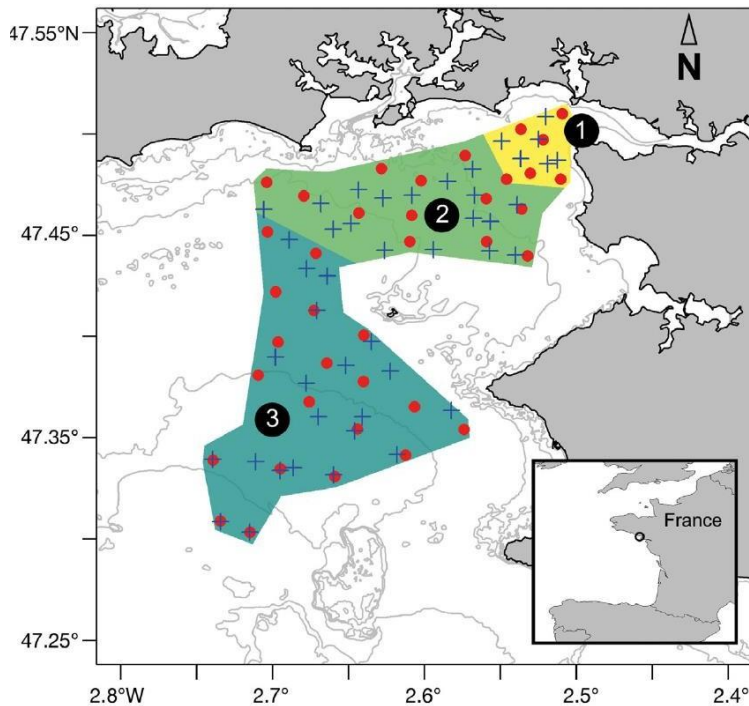


Fig. 2. Sampling design in the Bay of Vilaine. Red dots and blue crosses: grab and trawl sampling stations, respectively; 3 zones: the 3 main subtidal soft-bottom habitats along the bathymetric gradient. The C-shape of the area is due to a non-sampled rocky habitat on the east side of the bay

### 2.5.2. Survey data

A survey was performed in late September 2008 targeting juvenile fish and benthic macroinvertebrates. This season was selected because, for most of the local fish species, juveniles born in spring are large enough to avoid selectivity issues and size-dependent catch efficiency, and also because this period is just before their autumnal migration towards deeper grounds after the growth period (Dorel et al. 1991, Le Pape et al. 2007). Both protocols are detailed in Tableau et al. (2015). For fish sampling, most of the catches corresponded to benthic and demersal juvenile fish species belonging to the age groups 0 and 1 yr (G0 and G1). Fish species feeding at least partially on benthic macroinvertebrates were selected for this case study: 3 flatfish (benthic) species (*Solea solea*, *Dicologlossa cuneata*, and *Pleuronectes platessa*) and 4 roundfish (benthic or benthopelagic) species (*Merlangius merlangus*, *Merluccius merluccius*, *Mullus surmuletus*, and *Trisopterus luscus*). They represent 71% of the total fish abundance in this area. Ninety-four taxa were considered potential prey for the benthivorous fish community based on gut content analyses. They represent 96% in weight of the collected benthos. See Tableau et al. (2015) for further details on that selection.

### 2.5.3. Data inputs

Data and parameters are shown in Table 1. The detailed methodology for each data component is fully detailed in Supplement S2. Out of 14 parameters used to compute FC, 6 are described using the conservative approach, i.e. we select the value of the data or parameter leading to a minimal EE. For FP, 1 parameter out of 6 used the conservative approach.

## 3. RESULTS

### 3.1. FP and FC

The total FP in 2008 averaged over the 3 zones was 8120 MJ ha<sup>-1</sup> yr<sup>-1</sup> (~812 kJ m<sup>-2</sup> yr<sup>-1</sup>) and varied from 5850 to 8620 MJ ha<sup>-1</sup> yr<sup>-1</sup> among zones (Fig. 3a). When that FP is weighted by the accessibility coefficient (i.e. AFP), it is lowered to an average of 1110 MJ ha<sup>-1</sup> over the 3 zones (Fig. 3b), corresponding to 14% of total FP.

The spatial distribution of the FC (Fig. 3c) is more contrasted than the AFP (e.g. 2 times higher in zone 3 than in zone 2). Total FC in 2008 averaged among the 3 zones is estimated at 485 MJ ha<sup>-1</sup> yr<sup>-1</sup> for the whole bay.

The main consumers are 2 exclusive benthivorous fish cohorts (G1 [1-yr age group] of *Solea solea* and G1 of *Dicologlossa cuneata*) and 2 partial benthivorous cohorts (G0 of *Trisopterus luscus*, and G0 of *Merlangius merlangus*). The consumption of the G0 of *S. solea* and G0 of *Pleuronectes platessa* is concentrated in zone 1, which is a shallow area (5 to 13 m depth).

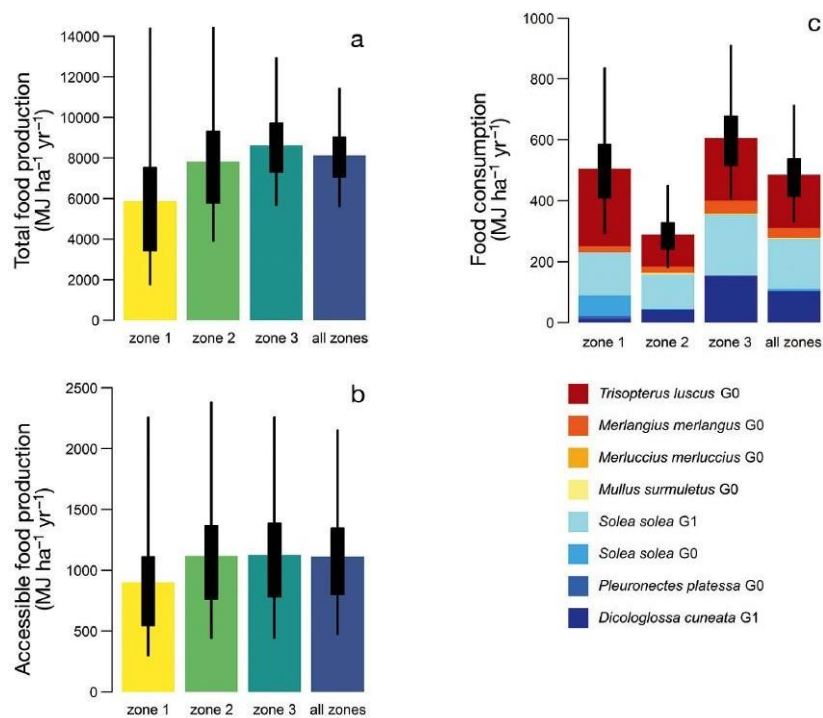


Fig. 3. (a) Total and (b) available food production and (c) food consumption, displayed by fish cohort (G0: young of the year; G1: 1 yr old) in the bay of Vilaine. Boxes: 50% confidence intervals; lines: 95% confidence intervals

### 3.2. EEs

The EE (Fig. 4) of the main benthivorous species (*S. solea*) on total FP is 2.1%. When all benthivorous species are considered, the estimate is 3.5% and increases to 6.1% when partial benthivorous species are also included. When only AFP is considered, the estimate of EE is far higher, ranging from 17.7% for *S. solea* to 50.0% for all species. Uncertainties around these estimates are very large, especially when only AFP is considered.

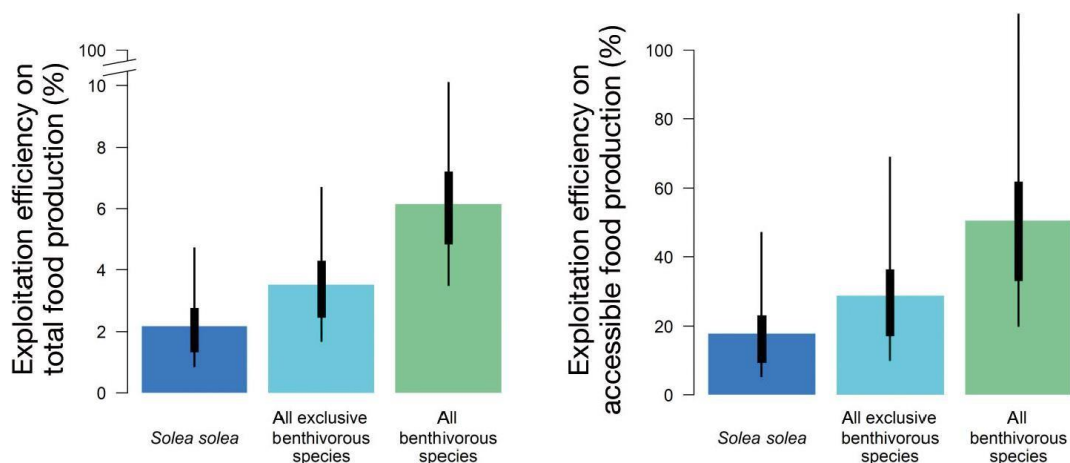


Fig. 4. Exploitation efficiency of total and accessible benthic production in 2008. Exclusive benthivorous species are the flatfish *Solea solea*, *Dicologlossa cuneata*, and *Pleuronectes platessa* and the roundfish *Mullus surmuletus*. All benthivorous species include also *Merluccius merluccius*, *Merlangius merlangus*, and *Trisopterus luscus*. Boxes: 50% confidence intervals; lines: 95% confidence intervals

## 4. DISCUSSION

This study demonstrates a method of computing the EE of fish juveniles feeding on benthic prey in nursery habitats. Properly estimating EE is essential to better understand the functioning of marine ecosystems (Libralato et al. 2008, Watson et al. 2014), and more specifically, to investigate the food limitation hypothesis within fish nursery habitats (Le Pape & Bonhommeau 2015).

### 4.1. The food limitation hypothesis: preliminary insights

Coastal nursery habitats present generally high FP and a refuge from predators (Wouters & Cabral 2009, Ryer et al. 2010, Nash & Geffen 2012). The underlying aim of the food limitation hypothesis is to determine predation pressure in order to understand the level of food limitation (Le Pape & Bonhommeau 2015). Defining different food limitation scenarios can help in interpreting the EE value for juvenile fish:

- No food limitation: food is abundant, and juvenile fish can invest negligible time and energy in foraging. The size of the juvenile population is either defined by factors affecting mortality in previous life stages (e.g. spawner condition affects offspring condition and survival, Hare 2014; larval predation, Houde 2008) or by other factors that occur during the juvenile stage (e.g. predation mortality, competition for space, Sheaves et al. 2015). Under the 'no food limitation' condition, the EE ( $EE_0$ ) varies over time (inter-annual independence between FP and FC) but remains close to 0. The reciprocal to this causal relationship is not always true: EE can be close to 0 at the scale of the entire nursery with food limitation that occurs locally if there is a lot of spatial heterogeneity of fish and prey distributions.
- 1<sup>st</sup> level of food limitation: FP supports normal growth of the juvenile fish community, but overdispersed prey force the fish to invest a significant amount of time and energy in foraging. This behavioral response increases the vulnerability of juvenile fish and, consequently, their mortality (Gibson 1994, Biro et al. 2003). This EE ( $EE_1$ ) is significantly above 0, but depends on density-dependent predation pressure (Johnson 2007, Cebrian 2015). This limiting effect, called predation-sensitive foraging (Sinclair & Arcese 1995) or risk effect (Heithaus et al. 2008), is typically a combination of food limitation and predation.
- 2<sup>nd</sup> level of food limitation: FP is temporarily not sufficient for all fish juveniles (van der Veer et al. 2016). Juvenile fish must invest a lot of time in finding food, and thus instantaneous vulnerability is exacerbated. One main difference between this and the 1<sup>st</sup> level of food limitation is that some individuals have a lower body condition and remain small. Paradoxically, a decrease of the apparent growth of the population is rarely observed even though this level of food limitation is suspected to occur frequently (Walters & Juanes 1993, Fiksen & Jørgensen 2011, Le Pape & Bonhommeau 2015). Indeed, small size implies vulnerability to predators that leads to size-dependent mortality (Sogard 1997), the apparent growth is thus maintained at a maximum. If this level of food limitation unfaillingly occurs, the EE ( $EE_2$ ) consistently, and over years, reaches a higher value than  $EE_1$  (which is, however, still unknown).
- 3<sup>rd</sup> level of food limitation: long-term FP is insufficient for juvenile fish. Consequently, individuals frequently starve to death (Gibson 1994). This has been verified in experiments (Edwards et al. 1970), but has not been observed in natural environments. Indeed, food deprivation in the wild, leading to poor condition, increases vulnerability to diseases and predation (Vethaak 1992) and leads to rapid and massive mortality (Juanes 2007) in the short term. This EE ( $EE_3$ ) is expected to reach values near 100% if all benthic invertebrate consumers are considered or if the EE is estimated from AFP when only juvenile fish are considered.

Consequently, juvenile fish communities are affected by the lack of food availability before full exploitation at the scale of the fish nursery (Heath 2005). Moreover, low EE does not exclude a high level of food limitation as predicted by the foraging arena theory (Walters & Juanes 1993). Indeed, high predation pressure on fish juveniles prevents them from leaving their shelter to reach better feeding areas and forces them to feed in very restricted areas that are then potentially overexploited. Nevertheless, as nursery habitats are considered to be shelters for juvenile fish (Gibson 1994, Wouters & Cabral 2009), EE could potentially be high. Thus, the remaining problem is to assess the thresholds of EE above which food limitation is temporarily (2<sup>nd</sup> level) or ongoingly (3<sup>rd</sup>) insufficient (i.e.  $EE_2$  and  $EE_3$ , respectively). The 3<sup>rd</sup> level could be reached before an EE of 100%. Indeed, significant levels of exploitation below 100% could lead to a collapse in prey availability. For instance, the uptake of 50% of the available production in an ecosystem (e.g. combination of invertebrate species and shellfish farming on primary production; Arbach Leloup et al. 2008) could lead to a dramatic shift in the trophic chain and a strong limitation of food availability for natural consumers (Raimonet & Cloern 2017).

Moreover, considering the widely studied fisheries exploitation, the sustainable level of EE at an ecosystem scale is estimated to be around only 15% (Libralato et al. 2008, Watson et al. 2014, Zhou et al. 2015). At this rate, transfer efficiency of benthic production in shallow coastal and estuarine nursery grounds could be limited (Arbach Leloup et al. 2008, Raimonet & Cloern 2017). The specificities of the communities of these ecosystems, i.e. the quality paradox (Elliott & Quintino 2007), with a large number of immature individuals and high levels of mortality, leads to moderate sustainable levels of transfer losses, and thus low potential EE. As these considerations concern overall EE, including predation by competitors, the maximal level of EE by juvenile fish is probably dramatically lower (see Table 2), far below 100%.

The estimates established in the Bay of Vilaine suggest that at least the 1<sup>st</sup> level of food limitation occurred in 2008. The spatial overlap between the biomass of the juvenile fish community and FP (macrobenthic prey) over the Bay of Vilaine (Tableau et al. 2016) supports this hypothesis. The high EE estimate on AFP suggests that the 2<sup>nd</sup> level of food limitation might be reached in some sectors of the bay. The potentially large underestimation of the level of EE and previous considerations on the likely moderate threshold of lasting food limitation (i.e. EE<sub>3</sub>) lead us to conclude that the 3<sup>rd</sup> level of food limitation could potentially be reached. An investigation over several years would be required to determine if there is consistency over time. The large uncertainties estimated in the present study would be drastically reduced by conducting at least 2 surveys (at the beginning and end of the main growth period) instead of one, as this increase in data would provide better estimates of fish growth, fish mortality (Nash & Geffen 2000), average benthic invertebrate biomass (Saulnier et al. 2019), and accessibility coefficients. Even if the food limitation hypothesis is investigated at the fish community scale, we assume that the density- dependent response to a lack of food availability would vary from one fish species to another. For instance, we expect that an exclusive benthic feeder would be more sensitive to a lack of benthic invertebrate availability than a partial benthic feeder, which can adapt its diet.

#### 4.2. Conservative (under)estimation of EE

The proposed method provides an estimate of the EE that integrates available ecological knowledge about the various species included in this case study. Input values can be derived either from *in situ* data (whenever possible) or from the literature. With regards to the assessment of their reliability, they are either fixed values or defined as statistical distributions. Unfortunately, available information on some uncertain parameters is too scarce and/or unreliable to define a statistical distribution. This limitation was overcome by using a conservative approach. Parameter values were chosen to provide a minimum estimate of FC. Improving these parameters would bring the estimate closer to the actual EE. Several other shortcomings of the approach lead to an underestimation of EE:

- Fish biomass: the use of a beam trawl minimizes the uncertainty of benthic and juvenile fish catch per trawled area (Dorel et al. 1991). However, estimation methods used in the literature often only provide maximum catch efficiencies (e.g. Reiss et al. 2006), thus minimum estimates of fish biomass. Moreover, fish species selected in the analysis account for 71% of the catch, not the overall amount that fish consumed.
- One parameter using the conservative approach is diet composition. Macrobenthic proportion in the diet is defined with the smallest values observed in the literature (Supplement S2). A source of underestimation of FC is that some fish cohorts are present in the bay only during one season. Consequently, they are not observed in some surveys, and are therefore not considered (e.g. G1 of *Pleuronectes platessa* in early summer, Desaunay et al. 1981). Moreover, the considered growth period is restricted to a time window corresponding to only the maximum growth period (Hamerlynck & Hostens 1993). Feeding activity during the winter period is not estimated. Juveniles of the selected species move progressively to deeper water in winter, but the corresponding consumption during this migration cannot be estimated as the apparent mortality rate (reflecting both mortality and migration rates) is not available. Consumption by the resident fish species, present in the remaining 29% of the survey catch, likely occurs (Fonds et al. 1992).
- The consumption of benthic production was estimated for fish species only, whereas other non-fish consumers (e.g. the brown shrimp *Crangon crangon*), sometimes occurring at high biomass, may also feed on the same pool of prey (Jung et al. 2017).
- The parameter converting energy production into energy consumption is defined and does not account for indigestible parts of ingested prey.

All of these shortcomings most likely lead to an underestimate of FC occurring in the natural environment. The actual EE value is higher than the estimate provided. This (under)estimate is valuable in the context of the food limitation hypothesis, but associated conclusions need to account for this conservative methodology.

#### **4.3. Community scale and prey accessibility: 2 keys of investigation**

The 2008 FP in the bay of Vilaine is in the production range of similar habitats (Burd et al. 2012, Bolam et al. 2014). When only the dominant benthivorous species is considered, the EE on the FP is low (~2%). This result is in the range of studies focusing on a single fish species (Table 2). However, since the carrying capacity of a population is determined by the strength of interspecific density-dependence (Brown et al. 2019), a community approach was adopted. When more of the benthivorous fish community was considered, the EE was far higher (~6%). This result underlines the need to account for a maximum of species preying on the same community (Vinagre & Cabral 2008). The EE of the juvenile fish of the selected species is in the range of the results of Ecopath applications in nursery habitats (Table 2). However, these models were not built to assess the food limitation hypothesis and face several shortcomings (i.e. the total biomass of a fish species is sometimes estimated from trawl catch without accounting for the catch efficiency, Rybarczyk & Elkaïm 2003); the lack of knowledge regarding production-to-biomass ratios for juvenile fish is also a major concern (Mackinson & Daskalov 2007). The present estimate of EE is also close to Pihl (1985), who used a similar approach in a more restricted area (1.5 ha; Table 2).

Pihl (1985) also stated that the production of some prey species is fully consumed and that half of total prey production is consumed (Table 2), suggesting food competition, and consequently, potential food limitation. Similarly, the Ecopath-based approach estimates the overall EE as ranging from 20 to 99%. This indicates that considering the juvenile fish community is relevant, but not sufficient, as other predators may feed on the same pool of prey. The EE estimates would thus benefit from considering additional megabenthic invertebrate consumers, such as large echinoderms (e.g. starfish *Asterias rubens*) or crustaceans (swimming crab *Liocarcinus holsatus*, and the brown shrimp *Crangon crangon*). However, some key parameters referring to these species, such as the gross conversion efficiency, are unknown, which prevents the inclusion of such consumers in this application.

Van der Veer et al. (2016, p. 105) emphasized that 'for a predator only harvestable prey matters'. Even though some prey species belong to the hyperbenthos, a large part of the benthic macrofauna live partly or totally burrowed in the sediment, so access to prey items is a factor that potentially heavily impacts the food quantity that is harvestable by juvenile fish (Tableau et al. 2015). Indeed, the EE could never reach 100% even if juvenile fish were the only consumers. Considering total FP instead of AFP would fail to test the food limitation hypothesis (Vinagre & Cabral 2008). To our knowledge, this study is the first attempt to investigate the food limitation hypothesis by accounting quantitatively for food accessibility. The application to the bay of Vilaine in 2008 shows that at least 20% of the FP accessible to juvenile fish is consumed, and does not exclude that the entire accessible production is consumed (cf. the uncertainty intervals; Fig. 3). Accounting for prey accessibility significantly increases the EE estimate by including additional information that is essential to investigate the food limitation hypothesis. The accessibility coefficient provided by Tableau et al. (2015) is, however, a large source of uncertainty and requires further investigation (e.g. seasonal prey availability and ontogenetic variations, Beukema et al. 2014, van der Veer et al. 2016; species-specific behavior, de Groot 1969).

Table 2. Estimates of exploitation efficiency (EE; ratio of benthic production consumed by their predators to the total benthic production) in temperate marine ecosystems: habitat, scale, number of species, method, habitat features (area, bathymetry) and location

| Main scale production of food estimation | No. of fish cohorts / species | Method of food consumption estimation | Surface area (ha) | Bathymetry (m) | EE by fish (%) | EE by all consumers (%) | Location                | Study                     |
|--|-------------------------------|---------------------------------------|-------------------|----------------|----------------|-------------------------|-------------------------|---------------------------|
| <b>Nursery habitat</b>                   |                               |                                       |                   |                |                |                         |                         |                           |
| Species                                  | 7                             | Bioenergetics                         | 19351             | 5–30           | 6.2            | ?                       | Bay of Vilaine, France  | This study                |
| Species                                  | 3                             | Evacuation rate                       | 1.5               | <1             | 6.8            | 50.8                    | Gullrnarsvik, Sweden    | Pihl (1985)               |
| Taxonomic groups                         | 2                             | Evacuation rate                       | 2400              | 1.6            | <1.0           | ?                       | Tagus estuary, Portugal | Vinagre & Cabral (2008)   |
| Taxonomic groups                         | 1                             | Evacuation rate                       | 4600              | 4.4            | <1.0           | ?                       | Tagus estuary, Portugal | Vinagre & Cabral (2008)   |
| Ecological guilds                        | Whole fish community          | Bioenergetics (Ecopath)               | >10 000           | ?              | 24             | 99                      | Narragansett Bay, USA   | Monaco & Ulanowicz (1997) |
| Ecological guilds                        | Whole fish community          | Bioenergetics (Ecopath)               | >10 000           | ?              | 4              | 99                      | Delaware Bay, USA       | Monaco & Ulanowicz (1997) |
| Ecological guilds                        | Whole fish community          | Bioenergetics (Ecopath)               | >10 000           | ?              | 11             | 94                      | Cheasapeake Bay, USA    | Monaco & Ulanowicz (1997) |
| Ecological guilds                        | Whole fish community          | Bioenergetics (Ecopath)               | 650 000           | 0–20           | 10             | 78                      | Seine Bay, France       | Tecchio et al. (2015)     |
| Ecological guilds                        | Whole fish community          | Bioenergetics (Ecopath)               | 450 000           | 0–10           | 1              | 20                      | Gironde estuary, France | Lobry et al. (2008)       |
| Ecological guilds                        | Whole fish community          | Bioenergetics (Ecopath)               | 5000              | 0 (intertidal) | 6.9            | 76                      | Bay of Somme, France    | Rybarczyk et al. (2003)   |
| Ecological guilds                        | Whole fish community          | Bioenergetics (Ecopath)               | 3500              | 0–5            | 18             | 72                      | Seine estuary, France   | Rybarczyk & Elkaïm (2003) |
| <b>Adult habitat</b>                     |                               |                                       |                   |                |                |                         |                         |                           |
| Species                                  | 2                             | Bioenergetics                         | 3.6               | <1             | 9              | ?                       | Kvarnbukten Bay, Sweden | Evans (1983)              |

#### 4.4. Future considerations

Moving forward, it would be fruitful to compare EE between nursery habitats over time, especially in areas with large differences in juvenile fish abundance. Indeed, as an EE value of 100% is unlikely, EEs significantly different from 0% and consistent among nursery habitats with contrasted fish juvenile abundance would support a general food limitation effect. In this context, the environmental factors influencing benthic invertebrate production may also contribute to density-dependent survival explaining recruitment variations (Salen-Picard et al. 2002). As predators of juvenile fish influence fish juvenile densities, EEs could provide indirect information about these predators. According to the foraging arena theory applied to 2 nurseries monitored over several years, the maximum EE value reached in a nursery more exposed to large predators is expected to be lower than in the more protected nursery. Therefore, the maximum EE value for a nursery over a time series would reflect the quality of shelter of that nursery from predators of the juvenile fish.

The present method was developed to test the food limitation hypothesis in a temperate coastal nursery context, but this framework is sufficiently generic and could be applied to a broad latitudinal range of coastal habitats (tropical, subarctic). However, parameters that vary with latitude (e.g. duration of growth period, Freitas et al. 2012) and/or at small spatial scales (e.g. growth rate, Ciotti et al. 2014), would have to be properly defined.

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# Novel approach for testing the food limitation hypothesis in estuarine and coastal fish nurseries

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## Supplement S1: Statistical distribution of the uncertain parameters

The variance ( $V$ ) and the mean ( $E$ ) of literature data are used to define a beta distribution for ratio parameters (comprised between 0 and 1), and a gamma distribution for the strictly positive parameters. The relationships between the variance ( $V$ ) and the mean ( $E$ ) of data to the shape parameters of the beta distribution ( $\alpha$  and  $\beta$ ), and to the shape ( $\alpha$ ) and rate ( $\beta$ ) parameters of the gamma distribution are:

beta distribution coefficients: 
$$\alpha = \frac{E(E-E^2-V)}{V} \quad (S1.1)$$

$$\beta = \frac{(1-E)(E-E^2-V)}{V} \quad (S1.2)$$

gamma distribution coefficients: 
$$\alpha = \frac{E^2}{V} \quad (S2.1)$$

$$\beta = \frac{E}{V} \quad (S2.2)$$

A parameter defined as a variable  $X$  whose logarithm is normally distributed (with a known mean:  $E$  and a known variance:  $V$ ) follows a log-normal distribution, which is directly defined by  $E$  and  $V$ . The mean ( $E'$ ) of  $X$  can be expressed in function of the mean ( $E$ ) and variance ( $V$ ) of  $\log(X)$ :

mean of lognormal distribution: 
$$E' = e^{(E+\frac{V}{2})} \quad (S3)$$

An exception is applied to the parameter  $K$ , which is in the denominator of the consumption equation. Indeed, if  $K$  follows a beta distribution, the distribution of  $1/K$  is unknown and has an unstable mean.  $K$  is thus defined with a gamma distribution. Therefore,  $1/K$  is defined as an inverse gamma distribution, which is defined by the shape ( $\alpha$ ) and rate ( $\beta$ ) parameters of the  $K$  distribution. The mean ( $E'$ ) of  $1/K$  can be expressed in function of the mean ( $E$ ) and variance ( $V$ ) of  $K$ :

mean of inverse gamma distribution: 
$$E' = \frac{E}{(E^2-V)} \quad \text{with the constraint: } V < E^2 \quad (S4)$$

## Supplement S2: data collection for the Bay of Vilaine

### Survey data

#### *Macrobenthic invertebrate biomass and fish abundance*

Given the mismatch in the locations of the sampling stations between the two surveys (fish and invertebrates) and the uneven spatial distribution of the sampling effort, we stratified the bay of Vilaine in three zones (Figure 1, which is a simplification of the 5 habitats defined by Kopp et al. 2013). Splitting is necessary because the sampling efforts of fish and benthic invertebrates decrease from zone 1 to zone 2, and zone 3 (respectively 3.4 stations.km<sup>-2</sup>, 2.0 stations.km<sup>-2</sup>, and 1.5 stations.km<sup>-2</sup> for fish sampling; and respectively 0.42 stations.km<sup>-2</sup>, 0.17 stations.km<sup>-2</sup>, and 0.17 stations.km<sup>-2</sup> for benthic invertebrate sampling). Therefore, for each cohort/species, the average abundance/biomass is computed in each zone and raised to the surface area to provide a total abundance/biomass. Bootstrap method is used to estimate the uncertainty on total abundance/biomass of each cohort/species.

#### *Fish weight-length relationships*

For each haul of the survey, fish are weighed by species all together, and they are all individually measured (a subsample is measured if the number exceeds 30 individuals). An observation is described as follows:

$$W_h = \sum_{n \in 1:N} a \cdot L_n^b \quad (\text{S5})$$

$W_h$  is the weight in g. of all individuals of a single species in the haul  $h$ ;  $L_n$  in mm is the length of the  $n^{\text{th}}$  fish individual;  $a$  and  $b$ , the parameters of the relationship. These parameters are then estimated using all observations with an optimization algorithm in the software R (R Core Team 2012).

Table S1: weight-length parameters (weight in g and length in mm)

| Species                      | a        | b     |
|------------------------------|----------|-------|
| <i>Dicologlossa cuneata</i>  | 3.028e-5 | 2.723 |
| <i>Pleuronectes platessa</i> | 1.369e-5 | 2.953 |
| <i>Solea solea</i>           | 9.237e-6 | 2.994 |
| <i>Mullus surmuletus</i>     | 7.636e-6 | 3.121 |
| <i>Merlangius merlangus</i>  | 9.749e-6 | 2.972 |
| <i>Merluccius merluccius</i> | 5.454e-6 | 3.055 |
| <i>Trisopterus luscus</i>    | 9.705e-6 | 3.054 |

## Literature data

### *Macrobenthic invertebrates*

Table S2: Summary of macrobenthic invertebrate parameters.

| Parameter                         | Value or range of values                           | Uncertainty details    | Source             |
|-----------------------------------|--|------------------------|--------------------|
| Conversion ratio (CR)             | 0.672  | sd=0.0111              | survey             |
| Production-to-biomass ratio (P:B) | 0.222-9.723 year <sup>-1</sup>                     | sd range: 0.0356-1.988 | (Brey 2012)        |
| Regeneration (R)                  | 0-0.5  | Conservative approach  | various sources    |
| Energy conversion (E)             | 0.851-6.694 kJ.g <sup>-1</sup>                     | Negligible uncertainty | (Brey et al. 2010) |
| Accessibility (A)                 | Easily accessible : 1<br>Hardly accessible : 0.117 | sd=0.0485              | survey             |

Additional details on these parameters are provided in Tableau et al 2015 for the 94 taxa.

## Fish juveniles

Table S3: Fish data compiled from the literature. \* As *Merluccius merluccius* shifts to an exclusive fish diet after 150 mm, this proportion becomes 0 for larger fish.

| fish                           | <i>Dicologlossa cuneata</i> | <i>Pleuronectes platessa</i> | <i>Solea solea</i>   | <i>Solea solea</i>   | <i>Mullus surmuletus</i> | <i>Merlangius merlangus</i> | <i>Merluccius merluccius</i> | <i>Trisopterus luscus</i> |
|--------------------------------|-----------------------------|------------------------------|----------------------|----------------------|--------------------------|-----------------------------|------------------------------|---------------------------|
| age group                      | G1                          | G0                           | G0                   | G1                   | G0                       | G0                          | G0                           | G0                        |
| shape                          | flatfish                    | flatfish                     | flatfish             | flatfish             | roundfish                | roundfish                   | roundfish                    | roundfish                 |
| diet                           | exclusive benthivore        | exclusive benthivore         | exclusive benthivore | exclusive benthivore | exclusive benthivore     | partial benthivore          | partial benthivore           | partial benthivore        |
| <b>Ld<sub>0</sub> (mm)</b>     | 110                         | 70                           | 70                   | 110                  | 70                       | 70                          | 70                           | 70                        |
| <b>d0</b>                      | April 11                    | August 7                     | July 31              | May 21               | August 11                | July 12                     | April 9                      | July 9                    |
| <b>G (mm.day<sup>-1</sup>)</b> | 0.38                        | 0.51                         | 0.60                 | 0.60                 | 0.77                     | 0.79                        | 0.67                         | 0.83                      |
| <b>Z (day<sup>-1</sup>)</b>    | 0.0179                      | 0.0171                       | 0.0179               | 0.0179               | 0.0103                   | 0.00760                     | 0.00765                      | 0.00770                   |
| <b>q</b>                       | 0.257                       | 0.380                        | 0.257                | 0.257                | 0.500                    | 0.500                       | 0.500                        | 0.500                     |
| <b>DC</b>                      | 1                           | 1                            | 1                    | 1                    | 1                        | 0.5                         | 0.27*                        | 0.75                      |
| <b>E (kJ.g<sup>-1</sup>)</b>   | 5.78                        | 5.66                         | 5.78                 | 5.78                 | 6.88                     | 6.24                        | 6.24                         | 6.24                      |
| <b>E sd</b>                    | 0.618                       | 0.802                        | 0.618                | 0.618                | 1.69                     | 0.805                       | 0.805                        | 0.805                     |
| <b>K</b>                       | 0.197                       | 0.316                        | 0.197                | 0.197                | 0.312                    | 0.385                       | 0.385                        | 0.385                     |
| <b>K sd</b>                    | 0.0675                      | 0.0792                       | 0.0675               | 0.0675               | 0.0969                   | 0.0720                      | 0.0720                       | 0.0720                    |

### Growth period and growth rate

The main growth period of fish juveniles in temperate ecosystems is ranging from spring to fall and is very consistent over many fish species (Forest 1975, Gordon 1977, Desaunay et al. 1981, Van Der Veer et al. 1990, Hamerlynck & Hostens 1993, Shi et al. 1997, Amara 2004, Otxotorena et al. 2010). This is explained by lower food intake during winter (Zanuy & Carrillo 1985). By conservative approach, we focus only on the food intake during the main growth period in summer. As a growth decrease is generally observed during fall, we set the end of the growth period in our model on October 1 (early fall). For G0 fish, the beginning of the growth period is deduced from the growth rate and the fish size from which they eat on macrobenthic invertebrates (set at 70 mm, see Tableau et al. 2016). For G1 *Solea solea*, the length at the beginning of the growth period is associated to the length of G0 at the end of the growth period (11 cm), this is supported by the observations in Desaunay et al. (1981). As no G0 *Dicologlossa cuneata* are observed, we use the same length for G1 *Dicologlossa cuneata*. This assumption is supported by the observations in Forest (Forest 1975).

The growth rates can vary over time and among the nursery habitats (Ciotti et al. 2014). The general strategy was to use data corresponding to the closest habitats of the bay of Vilaine when no local data were available. When length time series were available, the match with the fish length observed in the survey was checked (Forest 1975, Gordon 1977, Desaunay et al. 1981, Van Der Veer et al. 1990, Hamerlynck & Hostens 1993, Shi et al. 1997, Amara 2004, Otxotorena et al. 2010). The conservative approach for the growth period limits the potential overestimation of the exploitation efficiency.

Table S4: growth data collection (G0 for young of the year and G1 for one year old)

| Species                      | Age group | Growth rate (mm.day <sup>-1</sup> ) | Source  | Comment   |
|------------------------------|-----------|-------------------------------------|---|---|
| <i>Dicologlossa cuneata</i>  | G1        | 0.38                                | Forest 1975                                   | graphic analysis on local data  |
| <i>Pleuronectes platessa</i> | G0        | 0.51                                | Amara 2004                                    | local data  |
| <i>Solea solea</i>           | G0        | 0.60                                | Marchand 1991                                 | local data  |
| <i>Solea solea</i>           | G1        | 0.60                                | Desaunay et al. 1981, Marchand 1991           | local data & graphic analysis on local data                                       |
| <i>Mullus surmuletus</i>     | G0        | 0.77                                | N'Da and Deniel 2005                          | data analysis on local data   |
| <i>Merlangius merlangus</i>  | G0        | 0.79                                | Hamerlynck and Hostens 1993                   | graphic analysis on external data - good match between lengths at the same period |
| <i>Merluccius merluccius</i> | G0        | 0.67                                | Kacher and Amara 2005, Otxotorena et al. 2010 | average on two local data   |
| <i>Trisopterus luscus</i>    | G0        | 0.83                                | Hamerlynck and Hostens 1993                   | graphic analysis on external data - good match between lengths at the same period |

## Mortality rate

The mortality rates vary among nursery habitats and over time (Iles & Beverton 1991). In the exploitation efficiency analysis, emigration and natural mortality can be confounded as it results in a decrease of food consumption anyway. Mortality rates are available only for two flatfish species and are used for the others. A single data is available for three roundfish species, the average of the two Gadiformes species (*Merlangius merlangus* and *Trisopterus luscus*) is used for *Merluccius merluccius*:

*Pleuronectes platessa* (51 data): mean = 0.0171 nb.day<sup>-1</sup> & sd = 0.0088 (Iles & Beverton 1991, Modin & Pihl 1994, Nash & Geffen 2012)

*Limanda limanda* (9 data): mean = 0.0187 nb.day<sup>-1</sup> & sd = 0.0103 (Iles & Beverton 1991)

*Mullus surmuletus* (1 data): mean = 0.0103 (N'Da & Deniel 2005)

*Merlangius merlangus* (1 data): mean = 0.0076 (Hamerlynck & Hostens 1993)

*Trisopterus luscus* (1 data): mean = 0.0077 (Hamerlynck & Hostens 1993)

As the survey is done around the middle of the growth period (August 22), errors in mortality rates have small consequences: an overestimated mortality would result in a higher consumption estimate on the time period before the survey, but a lower one on the period after the survey. As we want to estimate the exploitation on the full time period, the lack of accuracy of this parameter is acceptable.

### Catch efficiency

Catch efficiency data have been estimated in several studies on various flatfish species including *Pleuronectes platessa* and *Solea solea*. The catch efficiencies are most likely overestimated in these studies given the experimental protocols (e.g Kuipers 1975). Consequently, fish abundances are probably underestimated, which fits with the conservative approach. First, available data have been compiled per study and then averaged over the different studies. *Solea solea* value has been attributed to *Dicologlossa cuneata* given their close phylogeny (*Soleidae* family). Data on roundfish species are scarcer but conservative data are suggested for *Merlangius merlangius* and *Trisopterus luscus*. This data has been associated to the roundfish *Mullus surmulutus* and *Merluccius merluccius*.

Table S5: catch efficiency data

| Species                      | q      | Trawl          | Source                      |
|------------------------------|--------|----------------|-----------------------------|
| <i>Pleuronectes platessa</i> | 50.6 % | 2 m beam trawl | (Rogers & Lockwood 1989)    |
| <i>Pleuronectes platessa</i> | 28.4 % | 2 m beam trawl | (Kuipers 1975)              |
| <i>Pleuronectes platessa</i> | 39.5 % | 2 m beam trawl | (Kuipers 1975)              |
| <i>Pleuronectes platessa</i> | 33.5 % | 2 m beam trawl | (Edwards & Steele 1968)     |
| <i>Solea solea</i>           | 25.7 % | 2 m beam trawl | (Rogers & Lockwood 1989)    |
| <i>Merlangius merlangus</i>  | 50.0 % | 3 m beam trawl | (Hamerlynck & Hostens 1993) |
| <i>Trisopterus luscus</i>    | 50.0 % | 3 m beam trawl | (Hamerlynck & Hostens 1993) |

### Diet

The first age groups of the three flatfish species are exclusive benthivorous species (Amara et al. 2001, Le Loc'h 2004). *Mullus surmulletus* is also an exclusive benthivore (N'da 1992). Based on the gravimetric proportion of benthic invertebrate prey observed in gut contents of G0 *Merlangius merlangus* and *Trisopterus luscus* (Hamerlynck & Hostens 1993), the estimated proportions are 50 % and 75 % respectively. Based on Mahe et al. (2007), the proportions in the *Merluccius merluccius* diet of benthic invertebrates are averaged over three regions (27 %). As G0 *Merluccius merluccius* diet shifts from a mix of fish and benthic invertebrates to only fish around 15mm, the proportion is set to 0 after 150 mm (Le Loc'h 2004, Mahe et al. 2007).



## Energy density

An investigation has been done on all articles of the journals “Aquaculture”, “Aquaculture nutrition” and “Aquaculture research”. A complementary research in all journals has been done with the keywords “Body composition” “energy density”. The body composition is often described as a proportion of proteins, lipids, glycogen, and water. Energy conversion coefficients have been compiled from different studies (Brett & Groves 1979, Brafield 1985, Cho & Kaushik 1990, Jobling 1993).

Proteins: 23.7kJ.g<sup>-1</sup>

Lipids: 36.3kJ.g<sup>-1</sup>

Glycogen: 17.2kJ.g<sup>-1</sup>

Water: 0kJ.g<sup>-1</sup>

As adult body composition varies with the reproduction season, only juvenile data are used. Pelagic fish data are rejected as this kind of fish has a higher fat concentration. Data corresponding to fish fed with high fat food are rejected. All data referring only to the flesh or the liver were also rejected. Among the 186 data collected, 62 referring to the fish taxa *Gadidae*, *Perciformes*, *Pleuronectidae*, and *Soleidae* were used. The average and the standard deviation of the corresponding taxa are attributed to each species. 25 references are used (Pandian 1970, Holdway & Beamish 1984, Smith et al. 1986, Hidalgo et al. 1987, Costopoulos & Fonds 1989, Marais 1990, Imsland et al. 2000, Lee et al. 2003, Person-Le Ruyet et al. 2004, Dias et al. 2004, Rosenlund et al. 2004, Tibbetts et al. 2005, Rema et al. 2008, Borges et al. 2009, Silva et al. 2010, Ding et al. 2010, Gatta et al. 2011, Li et al. 2012, Marinho et al. 2014, Guerreiro et al. 2015, Bonvini et al. 2015, López et al. 2016, Zhang et al. 2016, Li et al. 2017, Salas-Leiton et al. 2017).

## Gross conversion efficiency (growth-to-food intake ratio)

An investigation has been done on all articles of the journals “Aquaculture”, “Aquaculture nutrition” and “Aquaculture research”. A complementary research has been done in all journals with the keywords “growth efficiency energy”, “gross growth efficiency energy”, “gross conversion efficiency energy”, “food conversion efficiency energy”, “feed conversion efficiency energy”. Data collected in winter are rejected as lower temperature gives lower conversion efficiency (e.g. Zanuy & Carrillo 1985). When conversion efficiency data are estimated on a temperature gradient, we take only values around the optimal temperature. When data refer to weight conversion efficiency, we convert the production and the consumption in energy when possible. Gross conversion efficiencies are higher for young fish as no energy is allocated to reproduction. Thus, we use only gross conversion efficiencies referring to fish juveniles (Mateo 2007). We used 189 data referring to the fish taxa *Gadidae*, *Perciformes*, *Pleuronectidae*, and *Soleidae*. As these data mostly come from aquaculture studies, they are expected to be a bit higher than the gross conversion efficiency occurring in natural environment. The exploitation efficiencies are consequently likely underestimated. The average and the standard deviation of the corresponding taxa are attributed to each species. 31 references are used (Pandian 1970, Edwards et al. 1972, Marais & Kissil 1979, Hidalgo et al. 1987, Fonds et al. 1992, Hamerlynck & Hostens 1993, Lankford & Targett 1994, Buckel et al. 1995, Björnsson & Tryggvadóttir 1996, Deacon & Hecht 1999, Imsland et al. 2000, Kim & Lall 2001, Kim et al. 2001, Peck et al. 2003, Person-Le Ruyet et al. 2004, Dias et al. 2004, Rosenlund et al. 2004, Tibbetts et al. 2005, Mateo 2007, Rema et al. 2008, Borges et al. 2009, Silva et al. 2010, Ding et al. 2010, Gatta et al. 2011, Guerreiro et al. 2012, Li et al. 2012, Bonvini et al. 2015, López et al. 2016, Zhang et al. 2016, Li et al. 2017, Salas-Leiton et al. 2017).

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