Selection of marine fish for Integrated Multi-Trophic Aquaponic production in the Mediterranean area using DEXi multi-criteria analysis

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ABSTRACT

Producing food according to the sustainability and “circular economy” principles is considered a strategic goal by several world Institutions. Integrated Multi-Trophic Aquaculture (IMTA) responds to these criteria and stemming from it, the “Self-sufficient Integrated Multitrophic AquaPonic” (SIMTAP) aims to drastically reduce production inputs and waste outputs while maximizing the total food production. In order to succeed, proper selection of the most suitable fish, intermediate organisms and plant species to be grown in the system plays a fundamental role. To validate the SIMTAP concept and experimental prototype, the biological characteristics of fish and other species should be assessed taking into account their complementarity and adaptability to the physical and technical traits of the considered system.

This study aimed to identify the most suitable marine organisms for food production within the SIMTAP system and to create a decision model *via* the DEXi decision support system. Hence, in the present work a brief description of the SIMTAP concept, as well as the biological, zootechnical and commercial characteristics of several candidate fish species, are discussed. The criteria considered to address the species selection were: natural geo-distribution, domestication degree, environmental requirements, feeding regime, growth performances, and market value. The candidate species were: *Sparus aurata*, *Dicentrarchus labrax*, *Mugil cephalus*, *Diplodus puntazzo*, *Seriola dumerili*, *Umbrina cirrosa*, *Argyrosomus regius, Psetta maxima, Acipenser* spp., *Solea* spp, *Octopus vulgaris*. Finally, it seems that the DEXi approach increased the objectivity of the species selection process. Gilthead Sea Bream, European Sea Bass and Flathead Grey Mullet resulted to be the most suitable species for SIMTAP production.

Keywords: Fish, Integrated Multi-Trophic Aquaculture, Marine Aquaponics, Multi Criteria Analysis, DEXi, Sustainability.

1. Introduction

One of the Millennium Development Goals is the "eradication of extreme poverty and hunger" (WHO, 2000). To achieve this goal, global food production should be increased by more than 70% in the upcoming decades (Goddek et al., 2019). At the same time, food production will inevitably face other challenges, such as climate change and environmental pollution (Goddek et al., 2019). Moreover, the shortage of relevant primary resources, such as water and energy, are additional severe obstacles on this pathway.

Aquaponics (Ap) is a technique that combines hydroponics and aquaculture in an integrated system where fish and plants are cultivated in the same recirculating water body (Lennard and Goddek, 2019; Sommerville et al., 2014). Nitrogenous waste produced by the fish is transformed into nutrients for plants, thanks to the nitrification process lead by *nitrosomonas* and *nitrobacters* populating a biofilter (Sommerville et al., 2014). In brief, Ap can be described as an ecosystem where fish, plants, and bacteria live as symbionts and, thanks to the recycling of fish waste into plant nutrients, it contributes to the production of “sustainable” food. Moreover, Ap may usefully fit the arid regions or areas with non-arable soils (Goddek et al., 2019), and it is also proposed as a solution for marginal lands and urban agriculture, thereby, shortening the distance between producers and consumers (Goddek et al., 2019, 2015; Lampreia dos Santos, 2016).

Despite the synergism between bacteria and plants that ultimately reduces the concentration of water-soluble compounds (notably nitrates), solid fish wastes remain to be disposed of (e.g. faeces and uneaten feed) in an Ap system. A possible approach may be their harvesting and usage as food for other aquatic organisms such as molluscs or crustaceans (Barrington et al., 2009; Neori et al., 2004; Troell et al., 2003). Production systems that use this approach (Chopin, 2006) are called Integrated Multi-Trophic Aquaculture (IMTA). In an IMTA system, two kinds of organisms are considered: generating (fed) and cleaning (extractive) organisms. Generating organisms produce wastes from their activity (uneaten feed, faeces, etc.) while the extractives (plants or animals) convert these wastes into fertilizer, food and energy (Barrington et al., 2009; Troell et al., 2003).

1.1 The SIMTAP system concept and description

Stemming from IMTA, the Self-sufficient Integrated MultiTrophic AquaPonic system (SIMTAP) encompasses 4 trophic levels. This system is being developed within a H2020 PRIMA-Programme[1] and a brief description of the SIMTAP concept is given in Figure 1. In the SIMTAP system, micro-algae, detritivores and filter-feeder organisms (e.g. molluscs, crustaceans, polychaetes) may be used as feed for other aquatic organisms or even commercially exploited. This should drastically improve IMTA efficiency in terms of environmental sustainability and profitability while adhering more strictly to the circular economy principles (Barrington et al., 2009; Neori et al., 2004; Troell et al., 2003). The SIMTAP is also hypothesized for being coupled with hydroponic greenhouses, whose run-off effluents are rich in nutrients and can be profitably incorporated.

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Detritivores and filter-feeders are heterotrophic organisms such as polychaetes, bivalves and echinoderms, which convert organic sludge and micro-algae into nutritional biomass of animal origin. Autotrophic species are plants and algae: the plants and macro-algae are cultivated as in a traditional Ap, while micro-algae are decoupled and cultivated by an external source of nutrients and used to feed detritivores and filter-feeder organisms.

The water sources used for a generic SIMTAP production can be brackish (BR) or saltwater (SW) such as seawater, depending on the specific location, water availability and market opportunities. Freshwater (FW) Ap is the most widely described and practised worldwide, but in certain areas, the competition for FW may be a limiting factor. Moreover, marine fish are the most appreciated by the consumers (Gunning et al., 2016; Kotzen et al., 2019). Many studies reported the effects of BR or SW on fish and plant growth and, in general, the considered environmental parameters varied between studies. In detail, the temperature ranged between 19.1 and 27.9 °C (Boxman et al., 2017; Neori et al., 2000); salinity between 8 and 41 g/L (Boxman et al., 2017; Neori et al., 2000; Vlahos et al., 2019; Waller et al., 2015). Neori et al. (2000) set their system to obtain a final stocking density of 35 kg/m^3, much higher than those usually suggested for Ap production (Sommerville et al., 2014). Considering the above-mentioned experiences, in the Italy-based SIMTAP prototype, which this study refers to, salinity may range between 15 and 35 g/L, and the water temperature between 16-25 °C. The water exchange rate in the fish units will be set between 0.7 and 1.2 fish-tank volume per hour. The maximum fish stocking density is expected to range between 15 and 35 kg/m^3 when fish reach the commercial size (harvesting).

1.2 Fish species for SIMTAP production

As already mentioned above, several authors suggested that the fish (and the other extractive organisms) reared in the IMTA should possess certain biological and ethological characteristics compatible with the system’s conditions itself (Barrington et al., 2009). Under this perspective, since the SIMTAP is a marine-oriented production system and the Mediterranean market is the target which the project refers to, the candidate fish species should respond as much as possible to these “constraints”. Moreover, the SIMTAP production may also consider species belonging to other zoological classes that possess an adequate market value (e.g. molluscs and echinoderms). Amongst the fish species, Sturgeon (*Acipenser* spp.), Meagre (*Argyrosomus regius*), European Sea Bass (*Dicentrarchus labrax*), Sharpsnut Sea Bream (*Diplodus puntazzo*), Mullet (*Mugil cephalus*), Common Octopus (*Octopus vulgaris*), Turbot (*Psetta maxima*), Greater Amberjack (*Seriola dumerili*), Sole (*Solea* spp), Gilthead Sea Bream (*Sparus aurata*), Shi Drum (*Umbrina cirrosa*) may be considered as possible candidates. Selecting the most suitable species to be reared in the SIMTAP system implies the consideration of several additional aspects, and hence, a careful and specific study is necessary. For instance, features such as euryhalinity, eurythermality, feeding behaviours, reproduction physiology, ethological aspects among others, has to be carefully considered. After all, when BR and SW is used, euryhaline fish species and halophyte plants may contribute in increasing the number of possible organism combinations, thereby, enabling more convenient survival and growth rates of both fish and plants.

1.3 The DEXi multi-criteria analysis

Multi-criteria decision-aid (MCDA) or decision-making (MCDM) methods provide a systematic methodology to integrate heterogeneous and uncertain information with cost-benefit information and stakeholders views, in an understandable framework to rank project alternatives (Huang et al., 2011). MCDA could be classified under multiple-objective decision-making (MODM) and multiple-attribute decision-making (MADM) (Sadok et al., 2008). MODM includes methods that can be used in cases where there are infinite (continuous) or a large number of alternatives, based on multiple-objective mathematical programing models. On the contrary, MADM tools are used in cases of discrete, limited numbers of alternatives, characterized by multiple conflicting attributes (criteria). MADM tools are based on: a) the aggregation of judgments for each criterion and alternative; b) the ranking of the alternatives according to the aggregation rules (Sadok et al., 2008). DEX is a qualitative decision support methodology (Bohanec et al., 2013), belongings to the MADM group, implemented in the DEXi software (DEXi, 2020). The DEX approach divides decision-making problem into less complex sub-problems represented by criteria organized hierarchically. Each sub-problem is represented by a set of criteria that are first evaluated individually and linked to the utility function that evaluates each criterion in relation to its goal in the hierarchy (Craheix et al., 2015). DEXi differs from most conventional MADM tools since it uses qualitative (symbolic) instead of quantitative (numeric) attributes. Also, aggregation (utility) functions in DEXi are defined by “if-then decision” rules rather than numerically by weights or some other kind of formula. However, DEXi does support weights indirectly (Bohanec et al., 2013). DEXi is distributed as "freeware", fully functional software that can be used free of charge for all types of applications (DEXi, 2020).

As emphasized by several authors, the choice of the evaluation criteria and the structure of the hierarchical tree depend on the context and the designer’s visions of the analysed issue (Craheix et al., 2015). Therefore, results cannot be normalized, which implies representing both stakeholder preferences and the diversity of concerns associated with the system targeted (Craheix et al., 2015). Thus, the DEXi models are developed by defining (Bohanec et al., 2013): a) attributes: qualitative variables that represent decision sub-problems; b) scales: ordered or unordered sets of symbolic values that can be assigned to attributes; c) tree of attributes: a hierarchical structure representing the decomposition of the decision problem; d) utility functions: rules that define the aggregation of attributes from bottom to the top of the tree of attributes. In the evaluation and analysis stage, DEXi facilitates: 1) description of options: defining the values of basic attributes (terminal nodes of the tree); 2) evaluation of options: a bottom up aggregation of option values based on utility functions; 3) analysis of options: what-if analysis, "plus-minus-1" analysis, selective explanation and comparison of options, d) reporting: graphical and textual presentation of models, options and evaluation results.

1.4 *Vergara-Solana et al., (2019) listed the MCDA methods used within the aquaculture field. The authors displayed major research topics, where the MCDA has been applied to address aquaculture problems (Vergara-Solana et al., 2018). The production site selection is one of the most addressed questions in the context of MCDA in aquaculture (Esmaeilpour-Poodeh et al., 2019; Mahalakshmi et al., 2014; Vergara-Solana et al., 2018). Also, the selection of species for domestication is considered an interesting opportunity area for the use of MCDA methods (Tonissi Moroni et al., 2015; Vergara-Solana et al., 2018). DEXi is a widely used MCDM in the agricultural field for assessing environmental, economic and social sustainability of production systems (Bergez, 2013; Gendron et al., 2017; Hawes et al., 2019; Iocola et al., 2018; Karleuša et al., 2019; Montemurro et al., 2018; Rezaei et al., 2018). To our knowledge, there are no available applications of the DEXi method in relation to IMTA and Ap, so far.Aims of the study*

The main aim of the study was to individuate the most suitable marine fish species or other organisms to be reared in a SIMTAP prototype, considering its peculiar conditions, for sustainable food production purposes. At the same time, we aimed at creating a DEXi decision support model (DEXi_SIMTAP_Fish_1.0) adaptable to different geo-economic context.

2. Materials and Methods

The present study was carried out in the SIMTAP project framework (H2020 PRIMA S2 2018 project) at the Department of Veterinary Science (DSV) and the Department of Agriculture, Food and Environment (DiSAAA-a) of the University of Pisa (Italy). In order to address the selection of fish or other marine organisms for the experimental SIMTAP production, several attributes such as biological, economic, sustainability and social were considered. To this purpose, a panel of nine experts was selected. The members of the panel were representatives of the main scientific sectors involved in the SIMTAP project and notably engineering, aquaculture, aquaponics, hydroponics, marine biology, animal nutrition.

The decision process consisted of several consecutive steps. Firstly, a comprehensive analysis of the available literature was carried out on fish species considered as relevant for the

Italian SIMTAP production. Secondly, on the base of the collected data, the panel of experts performed the SWOT analysis for identifying the most relevant specie-related attributes to be considered in the decision process. Hence, the DEXi analysis was carried out in order to create the DEXi_SIMTAP_Fish_1.0 decision model and to define the tree of attributes and the utility functions rules ('weights'). To this regard, a "top-down" approach was used (Craheix et al., 2015). The criteria and indicators were chosen from the output of the SWOT analysis (Table 1), their weights were discussed among the members of the panel that eventually voted to take the final decision. In detail, the decision rules were defined by the 'weight' function ('Model' > 'Utility function' > 'Weight editor') of the software (Bohanec et al., 2013): the weight was expressed as a percentage (Table 3) in the 'Weight editor', then the software automatically assigned the value for the root criterion (Supplementary data) and the aggregated criteria. However, some decision rules had to be manually assessed: for the 'Fish species selection' criterion only 1.85% of the decision rules were determined by the panel of experts. The tree structure (Figure 2 and Table 2) consisted of one root criterion ('Fish species selection') branched into 2 not-aggregated and 4 aggregated criteria (2 indicators each):

I. 'Geo-distribution', refers to the wild distribution of the species in the Mediterranean Sea. It was considered as the starting point in the selection process since it may affect consumer acceptance. Therefore, considering that all the candidate species were autochthonous, the weight assigned to this criterion was low (4%).

II. 'Domestication' is an aggregated criterion composed of two indicators: 'know-how' and 'hatcheries availability'. 'Know-how' is referred to the available knowledge and technology related the culture of the considered species (reproduction, rearing techniques, etc.), while 'hatcheries availability' is referred to the presence and distribution of the hatcheries in the Mediterranean area as an indicator of juvenile availability. The overall weight of the criterion was 24% since it drastically affects the chances of rearing one species within the SIMTAP systems, while different weights were assigned to the indicators, 25% and 75% ('know-how' and 'hatcheries availability', respectively). In fact, the distribution of hatcheries and juvenile availability was considered as a highly important feature for the implementation of the system.

III. ‘Environmental needs’ is an aggregated criterion with ‘salinity’ and ‘temperature’ as the main indicators. Both these indicators influence the environmental adaptability of the species. This aspect is much more important when an IMTA system is built since it is necessary to match as much as possible to the environmental needs of each component of the system. The overall weight of the criterion was 24% while the indicators were considered as equally significant (50% each). The base for this evaluation was represented by the information obtained from the literature review.

IV. ‘Feeding regime’ is another aggregated criterion represented by two indicators; ‘wild feeding behaviour’ and ‘nutritional knowledge’. The first one was determined by the natural behaviour of the species, while the latter was based on the scientific knowledge achieved in the nutrition field. To this regard, the possibility of replacing marine by-products such as FM and FO with alternative protein and fatty acid sources was highly considered. The overall weight assigned to the criterion was 24% while the ‘nutritional knowledge’ was considered more relevant than ‘wild feeding behaviour’ (75 and 25%, respectively). In fact, one of the main goals of the SIMTAP is the use of “self-produced” detritivore and filter-feeder organisms as an alternative to FO and FM.

V. ‘Growth performances’ is a not-aggregated criterion and it refers to the time required to reach the commercial size. The weight assigned to this criterion was 20%.

VI. ‘Market value’ results from the aggregation of the two indicators *i.e.* ‘raw products’ and ‘processed by-products’. The overall weight of this criterion was 5% with different weights assigned to the indicators (25% for ‘processed by-products’ and 75% for ‘raw products’). This attribute was considered less influential in the decision process since the SIMTAP is currently under development and the commercial value of the final product was not considered as a priority.

For ranking each species, non-aggregated criteria and indicators were evaluated according to a two-value scale (‘High’ and ‘Low’), while aggregated criteria were evaluated according to a three-value scale (‘High’, ‘Medium’ and ‘Low’). Then, a five-value scale (‘Excellent’, ‘Good’, ‘Medium’, ‘Poor’ and ‘Unacceptable’) was adopted to score the root criterion for each considered species. In fact, the combination of the decision rules represents a trade-off between model simplicity and the accuracy of the final choice. The number of decision rules for the aggregated criteria was kept very low to limit the total number of rules, thereby avoiding its “combinatory explosion” (Craheix et al., 2015).

Finally, an evaluation of the relevance of the model structure was performed to estimate the accuracy of the decision process. To this purpose, the sensitivity analysis (Craheix et al., 2015) was performed by using the ‘plus/minus-1’ analysis tool of the 11 candidates (10 fish species and 1 cephalopod) (Bohanec et al., 2013).

3. Results

3.1 Summary of the literature analysis

An overall review of the candidate species is given according to their relevance in the Mediterranean aquaculture field.

3.1.1 Gilthead seabream (Sparus aurata)

Gilthead Sea Bream (GSB) belongs to the family of Sparidae and is one of the most common fish in the Mediterranean area (Cataudella and Bronzi, 2001; Oliva-Teles, 2000; Parisi et al., 2014; Sola et al., 2007). It is a euryhaline species, particularly during the initial stages of its life cycle (Basurco et al., 2011). The optimal temperature range is 18-26 °C, even though it may survive even between 4 and 32 °C (Bagni, 2005a; Cataudella and Bronzi, 2001; Moretti et al., 1999). It is a protandrous, hermaphrodite, species which naturally spawn during wintertime from October-December (Bagni, 2005a; Chaoui et al., 2006; Sola et al., 2007) and April when the water temperature raise to 13-17 °C (Basurco et al., 2011). GSB is mainly carnivorous (mussels, crustaceans, and fish) but accessorily herbivorous (Basurco et al., 2011; Cataudella and Bronzi, 2001). It is a demersal species, sedentary, solitary, or forming small aggregations (Basurco et al., 2011).

It is one of the most common farmed species in the Mediterranean area. The largest GSB producers in the Mediterranean area were Turkey (61,090 t in 2017), Greece (55,947.6 t), Spain (17,005.43 t) (EU, 2019). In Italy, 7,173.34 t of GSB was produced in 2017 with a slight increase compared to the previous year (EU, 2019). GSB is the most consumed fish by Italian consumers (30.6%). The wholesale weight of farmed GSB is 450-600 g (BMTI S.c.p.A, 2018). The EU production of GSB juveniles was 355.67 million in 2016: Greece was the largest producer (258.14 million), while Italian production of GSB juveniles in 2017 was about 91.8 million (EU, 2019).

The whole GSB life cycle can be conducted under controlled conditions and several breeding programs are already established in Spain, France and Greece (Martínez, 2017; Vandeputte et al., 2019). In farm conditions, juveniles are grown up to a commercial size of 2-3 grams before selling them (Moretti et al., 1999). Spawning can be induced after conditioning (temperature and photoperiod) and rarely GnRHa hormone injection is used (Bagni, 2005a). The on-growing phase is normally led both in sea cages or land-based tanks; in some cases, semi-extensive systems such as coastal lagoons are used, thanks to its considerable adaptability to different conditions (Basurco et al., 2011; Cataudella and Bronzi, 2001). GSB can successfully tolerate salinity level of 12 (Laiz-Carrión et al., 2005) and 28 g/L (Conides and Glamuzina, 2006; Klaoudatos and Conides, 1996), besides a full seawater salinity.

GSB is not a fast-growing species, it reaches the commercial size after 18-24 months or, in case of extremely favourable conditions, the grow-out phase can be completed within 10-15 months (Bagni, 2005a; Basurco et al., 2011; Cataudella and Bronzi, 2001; Parisi et al., 2014). Commercial diets are largely available in the form of extruded pellets with a 45–50% of crude protein (CP) and about 20% lipid content (Basurco et al., 2011; Cataudella and Bronzi, 2001). GSB can be successfully reared using fish meal (FM) and fish oil (FO) alternatives, for instance, on raw material such as plant and animal by-products (e.g. soybean meal, blood meal, etc.), while insect meal, macro- and micro-algae are in the process of being introduced in aquafeeds (Aragão et al., 2019; Basurco et al., 2011; De Francesco et al., 2007; Gasco et al., 2019; Martínez-Llorens et al., 2007; Pereira and Oliva-Teles, 2003; Santigosa et al., 2008).

In addition to the above-mentioned features, GSB is considered one of the most suitable species for SW or BR Ap, due to its euryhaline attitude (Fronte et al., 2016; Vlahos et al., 2019) but, research on this topic is very scarce. Neori et al. (2000) tested a SW Ap system where GSB were reared under 41 g/L salinity. Vlahos et al. (2019) studied the adaptation of GSB juveniles to a BR Ap environment at a salinity of 20 and 8 g/L and no differences were observed for final body weight (BW), length, specific growth rate (SGR), weight gain and survival rate. Therefore, based on these results the adaptation of GSB to BR or SW Ap is possible without compromising growth performances but a long-term exposure evaluation is necessary to confirm these results.

3.1.2 European seabass (Dicentrarchus labrax)

The European Sea Bass (ESB) belongs to the Moronidae family and is one of the most commonly reared species in the Mediterranean area (Cataudella and Bronzi, 2001; Moretti et al., 2005; Parisi et al., 2014). It is a euryhaline and eurythermal species that can tolerate a wide range of salinity (0.5-36 g/L) and temperature from 2 to 32 °C (Bagni, 2005b; Cataudella and Bronzi, 2001; Moretti et al., 1999; Parisi et al., 2014). The ESB is a gonochoric species and female growth performances are approximately 30% higher than in males (Fronte, 2010; Moretti et al., 1999; Parisi et al., 2014). The ESB shows seasonal reproductive behaviour, spawning 3-4 times from December to March (Bagni, 2005b; Moretti et al., 1999; Parisi et al., 2014). ESB is a predator and feeds on small crustaceans, small fish (about 1/4 of the diet), shrimps, and crabs (Moretti et al., 1999). The largest ESB producers in the Mediterranean area (EU, 2019) were Turkey (99,971 t in 2017), Greece (44,284.7 t), and Spain (17,655.9 t). In 2017, Italy produced 7,038.52 t of ESB with a slight increment compared to the previous years (EU, 2019). ESB is the fourth largest consumed fish (17%) by Italian consumers (BMTI S.c.p.A, 2018). The juveniles hatchery production was 234.9 million in 2016 of which Greece produced 163.32 million, 56.58 million in Spain and 10.61 million in Croatia (EU, 2019). Italian production in 2015 was 61.02 million and 28.7 million in 2017 (EU, 2019). In 2016, Turkey had produced more ESB juveniles (300 million) than any other European countries (EU, 2019).

The whole production cycle of ESB can be fully led under captivity conditions. When juveniles reach a BW of 2-5 g they can be stocked in the on-growing/fattening facilities (Moretti et al., 1999; Parisi et al., 2014). ESB can tolerate a wide range of salinity, however, better results in terms of growth were obtained under SW conditions (40 ppt). ESB showed high adaptability in FW (0.4 g/l) (Eroldogan et al., 2004), though the feeding rate was higher (Hunt et al., 2011). The suggested salinity range for optimal growth is 15-30 g/L (Conides and Glamuzina, 2006; Dendrinos and Thorpe, 1985; Saillant et al., 2003). Moreover, while the fish cultured in FW contains more lipids in comparison to those reared in SW (Eroldogan et al., 2004), increased levels of Polyunsaturated Fatty Acids (PUFA) and notably Docosahexaenoic acid (DHA, C22:6n-3) and Eicosapentaenoic acid (EPA, C20:5n-3) were found in SW-reared fish (Hunt et al., 2011). Regarding the rearing temperature, Person-Le Ruyet et al., (2004), reported that SGR increased up to a maximum at 25 °C and decreased from 29 °C; the maximum feed intake (FI) was observed between 25-29 °C and the highest Feed Efficiency Ratio (FER) between 19-25 °C.

ESB can be reared extensively in lagoons and/or ponds where it reaches the commercial size (350-500 g) in 24-37 months (Cataudella and Bronzi, 2001; Parisi et al., 2014). In land-based tanks rearing conditions, ESB can reach 350 g in 8-10 months (Bagni, 2005b; Cataudella and Bronzi, 2001; Parisi et al., 2014), or 350-500 g in 13-24 months in sea cages (Cataudella and Bronzi, 2001; Parisi et al., 2014). Commercial extruded diets for ESB are largely available and characterized by 45% CP and 9-18% of lipids (Cataudella and Bronzi, 2001). Also, ESB vegetable protein sources such as soybean meal or corn gluten meal are successfully used to replace 25-31% of FM (Ballestrazzi et al., 1994; Cataudella and Bronzi, 2001; Lanari and D’Agaro, 2016).

Moreover, ESB is considered a suitable species for being reared in a BR Ap system (Fronte et al., 2016) even though few studies are available. Waller et al., (2015) successfully led their study with ESB in a SW Ap environment (15-16 g/L), wherein during the 35-day experiment, fish (from 32 to 54 g) grew at SGR of 1.5 %/day and exhibited a feed conversion rate (FCR) of 0.93.

3.1.3 Mullet (Mugil cephalus)

Mullets belong to the Mugilidae family and 6 different species inhabits the Mediterranean area. Among them, the most represented species is the Flathead Grey Mullet (FGM) (Cataudella and Bronzi, 2001; Syama Dayal et al., 2017; Vallainc, 2016). It is a catadromous euryhaline species that live in the open sea, coastal lagoons, lakes, and rivers. It can survive at salinity ranging, from 0 to 75 g/L (Bagni, 2005c; Cardona, 2000; Saleh, 2008; Vallainc, 2016), even though significant differences in growth rate was observed (Ibanez, 2016; Saleh, 2008; Vallainc, 2016). During its life cycle, FGM tend to change places to minimize osmoregulation, thereby ensuring lower energy expenditure and as a consequence, the growth is higher (Cardona, 2006, 2000; Nordlie, 2016): a) Juvenile fish prefer FW (<1.0 g/L) and oligohaline (1.1-5.0 g/L) sites; (b) immature fish also prefer FW and oligohaline water although they avoid FW sites in winter and spring; c) adults always avoid FW areas, concentrating in polyhaline (15.1-30.0 g/L) sites during autumn and summer and move to euhaline (30.1-40.0 g/L) sites in winter and spring. FGM is an oviparous gonochoristic fish and females are slightly bigger than males (González-Castro, Mariano Minos, 2016; Vallainc, 2016). FGM is a synchronous spawning species with a single spawning cycle occurring from May to October when adults undertake a reproductive migration from estuaries or coastal lagoons to the sea (Cataudella and Bronzi, 2001; Koutrakis, 2016; Saleh, 2008; Vallainc, 2016). FGM is an omnivorous species and diurnal feeder: initially, larvae are usually planktonic feeder, the adults and juveniles feed on small invertebrates, benthic organisms and micro-algae (diatoms), as well as on the organic matter present in the sediment (Bagni, 2005c; Cardona, 2016; Vallainc, 2016). In 2013, the total aquaculture production of Mullets was 138,143 t worldwide (19.2% of world Mullet production), mainly (74%) from the BR environment (Crosetti, 2016). The same year, the largest worldwide producer of Mullet from aquaculture (116,151 t) was Egypt (Crosetti, 2016; Vallainc, 2016). Regarding European production, Greece was the largest producer in 2017 with 197.7 t (EU, 2019). Juvenile production was 1.09 million in the EU, the whole production covered by Spain (EU, 2019). The main outcome of Mullet production is the dried, salted, gonads called ‘bottarga’ (Koutrakis, 2016; Vallainc, 2016). The market price for ‘Bottarga di Cabras’ (Sardinia, Italy) is 100-

140 €/kg, approximately. Moreover, at harvest the weight of the ovary may range between 400 g and 600 g and its yield after processing may reach 62%.

The FGM aquaculture production is based on extensive systems. Juveniles are collected during spring when migrating towards lagoons or are captured in the wild and then released in ponds and lagoons (Cataudella and Bronzi, 2001; Vallainc, 2016). Over the last decades, the productivity of Mullet in lagoons has constantly decreased mainly due to the reduced migration of juveniles (Vallainc, 2016). The reproduction of mullets under farm conditions never reached a commercial scale due to the high hormone dosages required and the associated high running costs (Cataudella and Bronzi, 2001; Saleh, 2008; Vallainc, 2016). FGM is a fast-grower species and it can reach 0.75-1 kg BW in 7-8 months or 1.5-1.75 kg in the next two seasons (Saleh, 2008). Due to their feeding habits, FGM are successfully farmed in polyculture with other species (e.g. crustaceans) as secondary species or dominant to re-use organic matter produced by the other cultures. In 2015, Egyptian researchers started an IMTA Mullet production in association with the Prawn (*Macrobrachium rosenbergii*), where Mullets were fed on organic particulate from tilapia and catfish ponds (Koçak, 2015). In these type of culture, growth performances were better than those observed in intensive systems, despite the use of artificial feed (Cataudella and Bronzi, 2001; Saleh, 2008; Syama Dayal et al., 2017). Sommerville et al. (2014) indicated FGM as a common species cultured in Ap. The suggested optimal temperature for FGM Ap production is 20-27 °C (tolerating 8-32 °C) and CP diet level of 30-34 % (Sommerville et al., 2014).

3.1.4 Sharpsnut sea bream (Diplodus puntazzo)

The Sharpsnut sea bream (SSB) belongs to the Sparidae family and is considered as an excellent new species to be cultured (Basurco et al., 2011; Boglione et al., 2003; Cataudella and Bronzi, 2001; Favaloro et al., 2002). It is benthopelagic and euryhaline (Basurco et al., 2011; Cataudella and Bronzi, 2001), omnivorous and feeds on seaweeds, worms, molluscs and shrimps (Basurco et al., 2011; Favaloro et al., 2002; Parisi et al., 2014). It is a protandric hermaphrodite species (rudimentary hermaphrodite) (Basurco et al., 2011; Papadaki et al., 2008). The natural spawning occurs in autumn-winter when the water temperature range between 18.5-20 °C (Basurco et al., 2011).

Thanks to its omnivorous tropism and euryhaline attitude, SSB is the most common cultured Diplodus species, mainly extensively (Cataudella and Bronzi, 2001). In 2015 (EU, 2019; Parisi et al., 2014), the three major EU SSB producers were Greece (202.1 t), Turkey (59.0 t) and Italy (10.18 t), while juvenile production was recorded only in Greece (0.62 million) in 2016 (EU, 2019). SSB is suitable for polyculture with GSB or ESB because of its ability to feed on the bottom of tanks (land-based) or sea cages fouling (Cataudella and Bronzi, 2001; Favaloro et al., 2002; Parisi et al., 2014). Nevertheless, despite the occurrence of sexual maturation also in broodstock reared in captivity, spawning is restricted to wild individuals (Basurco et al., 2011). SSB adults and juveniles are usually reared in SW from 37.0 to 37.7 g/L, both in sea-cages or land-based tanks (Almaida-Pagán et al., 2007; Cerezo and García García, 2004; Faranda et al., 1985; Favaloro and Mazzola, 2006; Hernández et al., 2007, 2003, 2001; Orban et al., 2000; Piedecausa et al., 2007). However, natural nurseries for SSB are generally located in estuarine areas with low salinity, mud substrates and low dissolved oxygen (Vinagre et al., 2010). Growth performances were good but lower than those of GSB under intensive rearing conditions (Basurco et al., 2011; Cataudella and Bronzi, 2001). They are fed on artificial diets with 40-45% of CP and 20% of lipids, with a high inclusion rate (up to 60% of CP) of by-plant sources such as soybean meal, sunflower meal and other plant oils (Basurco et al., 2011; Hernández et al., 2007; Parisi et al., 2014; Piedecausa et al., 2007). The FO can be also replaced in SSB juveniles with soybean oil up to 75% of lipid content without compromising the growth (Nogales-Mérida et al., 2017). Nevertheless, the production of SSB has never reached a commercial scale so far, probably due to several difficulties in the production cycle (Boglione et al., 2003; Papadaki et al., 2008; Parisi et al., 2014). To our knowledge, no studies on Ap production has been carried out so far for *Diplodus puntazzo* and/or other *Diplodus* species.

3.1.5 Greater amberjack (Seriola dumerili)

Greater amberjack (GA) belongs to the Carangidae family and it is native of the Mediterranean Sea (Jerez Herrera and Vassallo Agius, 2016). GA is a pelagic-epibenthic fish (Jerez Herrera and Vassallo Agius, 2016). It is a carnivorous species that feeds on zooplankton, algae and polychaetes, benthic and nektonic organism, other pelagic fish, and cephalopods (Cataudella and Bronzi, 2001; Jerez Herrera and Vassallo Agius, 2016; Parisi et al., 2014). GA is a gonochoric species and in the Mediterranean, the adults (8-10 kg and 4-5 years old) spawn several times from May to July (Cataudella and Bronzi, 2001; Jerez Herrera and Vassallo Agius, 2016; Parisi et al., 2014).

GA is considered one of the most important candidates for aquaculture diversification, thanks to a possible adaptation to captivity conditions, high growth rate (600 g in 6 months or 6 kg in 2.5 years), excellent flesh quality and high market price (Fusari et al., 2010; Jerez et al., 2006; Mazzola et al., 2000; Papandroulakis et al., 2005; Parisi et al., 2014). However, high nutritional requirements, feeding habits, incidences of diseases, lack of genetic breeding programs, difficulties in sexual maturation and spawning under captivity conditions, are still relevant bottlenecks (Cataudella and Bronzi, 2001; Fernández-Palacios et al., 2015; Garcia-Gomez and Diaz, 1995; Jerez Herrera and Vassallo Agius, 2016; Mazzola et al., 2000; Micale et al., 1999; Mylonas et al., 2004b; Parisi et al., 2014; Roo et al., 2013; Sicuro and Luzzana, 2016). In 2017, the largest EU producers were Portugal (23.4 t) and Spain (11 t) and the hatchery production in 2016 was approximately 0.07 million (EU, 2019), just in Spain. GA culture is still mostly based on the capture of wild juveniles, even though captive reproduction is also possible using hormonal treatments (Jerez Herrera and Vassallo Agius, 2016; Jerez et al., 2006; Papandroulakis et al., 2005; Parisi et al., 2014). The optimal range for water temperature is 20-22 °C (Garcia-Gomez and Diaz, 1995; Jerez Herrera and Vassallo Agius, 2016; Mazzola et al., 2000). GA is usually reared in SW with salinity ranging between 34-38 g/L (Fernández-Palacios et al., 2015; Jerez et al., 2006; Jover et al., 1999; Mazzola et al., 2000; Micale et al., 1999; Papadakis et al., 2008; Papandroulakis et al., 2005; Talbot et al., 2000). The growing phase of GA juveniles is usually led in land-based or offshore facilities. Since precise GA nutritional requirements are not yet available (Cataudella and Bronzi, 2001; Garcia-Gomez, 2000; Garcia-Gomez and Diaz, 1995; Mazzola et al., 2000; Monge-Ortiz et al., 2018b; Sicuro and Luzzana, 2016) an optimal diet composition is not well defined yet. CP content of GA diets still varies from 42 to 50% and the main protein source is still FM with a very limited replacement rate with plants protein. Also, lipids content is quite variable from 10.5 to 14% despite a suggested requirement of 20 %, possibly with high HUFA rate (Haouas et al., 2010; Jerez Herrera and Vassallo Agius, 2016; Jover et al., 1999; Mazzola et al., 2000; Monge-Ortiz et al., 2018a, 2018b; Papadakis et al., 2008; Talbot et al., 2000). GA does not readily accept dry diets and frequently moist pellets or other raw material (fresh or frozen fish and scrap) are preferred (Parisi et al., 2014). There are no experiences about the application of *S. dumerili* in Ap.

3.1.6 Shi drum (Umbrina cirrosa)

Shi drum (SD) belongs to the family of Sciaenidae, is strongly euryhaline and naturally lives in the Mediterranean Sea (Cataudella and Bronzi, 2001; Chaves-Pozo et al., 2019). It is a multiple-batch group-synchronous summer spawner (June-August) when water temperature range between 22 and 26 °C (Mylonas et al., 2004a). SD is considered one of the most suitable species for the Mediterranean aquaculture, thanks to its characteristics as a summer spawner (limited competition for hatchery facilities with the widespread winter spawners species), high feeding efficiency, relatively easy adaptation to farm condition and interesting market price (Cataudella and Bronzi, 2001; Chaves-Pozo et al., 2019; Henry and Fountoulaki, 2014; Koumoundouros et al., 2005; Mylonas et al., 2004a). In 2017 the largest EU producer (157.9 tonnes) was Greece (EU, 2019) while juvenile production has not been recorded yet.

Spawning can be induced with a single injection of GnRHa (Koumoundouros et al., 2005; Mylonas et al., 2004a) or can occur naturally (Ayala et al., 2017), and thanks to its early digestive system development, SD larvae can be fed on artificial diets starting from 35 dph, approximately (Cataudella and Bronzi, 2001; Chaves-Pozo et al., 2019; Henry and Fountoulaki, 2014; Mylonas et al., 2009, 2004a). SD can easily adapt to full SW (40 g/L) or isosmotic water (10 g/L) without any osmoregulatory imbalance, although the acclimation in a FW environment is associated with reduced growth, FCR and SGR (Mylonas et al., 2009). Frequently, SD is cultured in land-based tanks supplied with BR water (25 g/L) (Grigorakis et al., 2016; Henry and Fountoulaki, 2014; Koumoundouros et al., 2005; Mylonas et al., 2004a; Segato et al., 2005). SD shows also a wide range of temperature tolerance, 16-26 °C (Grigorakis et al., 2016; Henry and Fountoulaki, 2014) and can be easily reared in polyculture, notably with grey mullets (Cataudella and Bronzi, 2001). As a fast-grower, SD can reach 650-700 g in 15-24 months or 360 g in 4 months if temperature ranged between 20 and 22 °C (Cataudella and Bronzi, 2001; Chaves-Pozo et al., 2019; Mylonas et al., 2004a). The recommended content in dried-pellet for SD is 47-52% of CP and 13% of lipids (Akpinar et al., 2012b, 2012a; Cataudella and Bronzi, 2001) and a partial FM and FO replacement (14% and 12% respectively) is possible using plant protein and vegetable oils (Segato et al., 2005). Similar to GA and SSB, no experiences about the application of *U. cirrosa* in Ap are available.

3.1.7 Meagre (Argyrosomus regius)

Meagre (ME) is a euryhaline fish belonging to Sciaenidae, widespread in the Mediterranean sea, although not very common in Italy (Parisi et al., 2014; Stipa and Angelini, 2005). ME is anadromous and it spawns from January to May (Parisi et al., 2014; Stipa and Angelini, 2005). It is carnivorous and initially feed on small demersal fish and crustaceans, then on pelagic fish and cephalopods (Parisi et al., 2014; Stipa and Angelini, 2005).

ME is considered a suitable species for the Mediterranean aquaculture diversification, thanks to its high adaptability to different environmental conditions and high resilience to stressors (Monfort, 2010; Parisi et al., 2014). Egypt is the biggest producer in the Mediterranean area (Parisi et al., 2014). In 2017, the ME European production was 5,510 t; the larger producers were (EU, 2019) Spain (3,523.69 t) and Greece (1,634 t). In 2016, 2.67 million juveniles were produced in Europe, 2.54 million in Spain (EU, 2019). ME is a very well domesticated species and its culture can be fully led in captivity. Spawning can be induced by hormonal (GnRHa) treatments (Duncan et al., 2008). The optimal salinity of ME ranges between 31-39 g/L, very close to SW value (Chatzifotis et al., 2012, 2010; Piccolo et al., 2008; Roo et al., 2010) but no studies have been carried out at lower salinity. ME can tolerate a wide range of temperatures, for instance from 14 to 23 °C, and temperature from 17 to 21 °C is considered as the optimal range (Parisi et al., 2014; Stipa and Angelini, 2005). The on-growing phase is led on both land-based tanks and sea cages. ME is a fast-growing species and under optimal conditions, it reaches the commercial size (700-1200 g) after 12 months only and weighs 2-2.5 kg after 24 months (Chatzifotis et al., 2012, 2010; Fountoulaki et al., 2017; Parisi et al., 2014; Stipa and Angelini, 2005). The optimal CP diet content range between 45-50%, while the optimal lipid content is 17% (Chatzifotis et al., 2012, 2010). Meagre showed a good ability to cope with plant-based diets (Emre et al., 2016; Ribeiro et al., 2015). Nowadays, the Italian consumption of ME is finally slowly expanding (Stipa and Angelini, 2005) and its strengths are the attractiveness of the fish shape, the good processing yield, the nutritional value and low-fat content, in addition to the good taste and firm texture of flesh suitable for a variety of processes and usage (Monfort, 2010; Parisi et al., 2014; Piccolo et al., 2008). However, the ME market demand is still limited due to competition with traditionally consumed fish, such as GSB, ESB, among others (Monfort, 2010; Parisi et al., 2014; Stipa and Angelini, 2005).

3.1.8 Turbot (Psetta maxima)

Turbot (TU) is a benthic flatfish that belongs to the Scophthalmidae family. It is carnivorous and mainly feed on crustaceans, molluscs and cephalopods (Rodriguez Villanueva and Fernandez Souto, 2005). It is a gonochoric species with a single spawning season that in the Mediterranean Sea goes from February to April (Rodriguez Villanueva and Fernandez Souto, 2005). TU is the largest farmed flatfish species. The European production was 11,516.64 t in 2017 of which 8,771.39 t was produced in Spain and 2,745.25 t in Portugal (EU, 2019). Despite this, aquaculture provides for 50% of the total TU European production (Bjørndal and Øiestad, 2011). In 2016, 8.45 million juveniles were produced in Spain (EU, 2019).

High temperature is the most important limiting factor that leads to a failure in Italian TU culture (Parisi et al., 2014). Another bottleneck is the availability of juveniles due to the complexity of early rearing, low survival before metamorphosis, and limited egg production. TU production is based on the possibility to obtain viable eggs naturally or by manipulation of photoperiod (16/8 light/dark) and temperature (13-15°C) and also by using pellets containing GnRHa (Parisi et al., 2014; Ruyet and Baudin-Laurenc, 1991). TU is usually reared in onshore tanks using raceways seawater system with high stocking density (Bjørndal and Øiestad, 2011; Parisi et al., 2014; Poxton et al., 1982; Rodriguez Villanueva and Fernandez Souto, 2005), a temperature of 14-22 °C (optimal 16 °C), and salinity of 20-35 g/L (Imsland et al., 2001; Parisi et al., 2014; Rodriguez Villanueva and Fernandez Souto, 2005; Ruyet and Baudin-Laurenc, 1991). To this regard, Imsland et al. (2001), observed an optimal FCR when the combination of temperature-salinity was 18.3±0.68 °C and 19.0±1.0 g/L, respectively. During on-growing phase fish are fed on artificial diet containing at least 60% of marine-based ingredients (Parisi et al., 2014; Ruyet and Baudin-Laurenc, 1991), with 50.5-51.0% of CP and 8-11% of lipids content (Leknes et al., 2012; Sevgili et al., 2015). Under optimal thermal condition (15-20 °C) they reach 0.5-2 kg of BW after 18-27 months (Ruyet and Baudin-Laurenc, 1991).

3.2 Other species (Sturgeon ssp., Sole ssp. and Octopus vulgaris)

Besides several limiting factors in terms of rearing techniques or still in the process of experimental rearing, Sturgeon ssp., Sole ssp. and *Octopus vulgaris* may be also be considered as candidate species for SIMTAP production.

Sturgeons (ST) belong to the Acipenseridae family that includes several species. In Italy, three species are considered as endemic (Parisi et al., 2014) *viz*. common sturgeon (*Acipenser sturio*), Beluga sturgeon (*Huso huso*) and Italian sturgeon (*Acipenser naccarii*). Despite the presence of these wild species, the most commonly reared species is the white sturgeon (*Acipenser trasmontanus*) which is an anadromous species as it migrates to FW from SW for spawning (Parisi et al., 2014). However, majority of the species live in BR water of estuarine habitats (semi-anadromous), for instance, the white ST (Doroshov, 1985; Doroshov et al., 1997; McEnroe and Cech, 1985). Wild female ST reaches sexual maturity in 15-32 years, while in captive conditions it may reach maturity in 6-14 years (Doroshov et al., 1997; Parisi et al., 2014). All STs are carnivorous and usually feed on molluscs, lampreys, shad, polychaetes (Doroshov, 1985). Farming technologies for STs in Italy is mainly based on FW raceways and ponds with a temperature ranging between 11-26 °C (Parisi et al., 2014). The environmental conditions significantly affect growth performance of white ST (Cech and Doroshov, 2004; Doroshov et al., 1997; Israel et al., 2009; McEnroe and Cech, 1985; Mojazi Amiri et al., 2009): a) maximum growth can be achieved using spring and summer photoperiod, b) adult female requires exposure to 10 °C for 3-6 months before spawning to stimulate oocyte development and ovulation, the optimal temperature for development and survival of embryos is 14-17 °C and juveniles grow faster at 20-25 °C, c) for adults, the preferred salinity is 22-26 g/L, juveniles can tolerate high-salinity levels (up to 15 g/L) while eggs and embryos are found in very low salinity(up to 0 g/L). STs are usually fed on artificial diets containing 40-45% of CP, 19-20 MJ/kg, often supplemented with Vitamin C (Parisi et al., 2014) but, they can be also be fed on frozen fish and shellfish during the final ovarian growth period (Parisi et al., 2014). Few research studies suggested that partial replacement of FM and FO was possible in the ST culture (Hung, 2017; Parisi et al., 2014). The main outcome from sturgeon culture is meat which ex-farm price is 2.5-3.2 €/kg, and the very appreciated caviar has an ex-farm price of 350-550 €/kg (Parisi et al., 2014).

Solea spp. (SO) is a group of demersal marine flatfish (Colen et al., 2014), mainly represented by two species *Solea solea* (Common Sole, CS) and *Solea senegalensis* (SS). Adults feed mainly on polychaete worms, molluscs and small crustaceans (Colen et al., 2014). The natural spawning period in the Mediterranean sea varies among the species (Colen et al., 2014; Imsland et al., 2003; Parisi et al., 2014): from January to May (CS) and May to August (SS). They are gonochoric species and SS reaches sexual maturity earlier than CS (Colen et al., 2014). Although SS is better adapted than CS to the warmer waters as compared to those of the temperate zones and is more suitable for aquaculture production, only CS is considered as autochthonous species (Colen et al., 2014; Dinis et al., 1999; Parisi et al., 2014).

The production of SS in 2017 was 1,187.67 t of live weight, mainly produced in Spain (1,012.39 t). Spain produced also 11.44 million of SS fingerlings in 2016 (EU, 2019). Thanks to their high market value (12-25 €/kg), SO is an optimal candidate for aquaculture diversification in Europe (Bjørndal et al., 2016; Parisi et al., 2014). The whole cycle can be completed under captivity conditions. Currently, standardization of the spawning schedule and feeding protocol represents the main bottlenecks (Parisi et al., 2014). Broodstocks are reared in large tanks supplied with recirculating SW (35 ± 0.6 g/L) and are fed on semi-moist pellets composed of squid and supplemented with polychaetes during final maturation phase (Dinis et al., 1999; Parisi et al., 2014). The larval feeding behaviour (initially pelagic, then benthic) represents one of the most critical phases of SO culture (Parisi et al., 2014) and is also the main cause for high-cost juveniles production (Bjørndal et al., 2016). Two systems are mainly adopted for the on-growing stage: land-based ponds for extensive and semi-intensive culture or shallow raceways for the intensive culture (Dinis et al., 1999; Parisi et al., 2014). SO are frequently reared in polyculture with GSB or ESB, since the presence of macrofauna very rich in polychaetes has been reported in commercial seabream ponds’ bottom (Dinis et al., 1999). SS when reared in warm SW (19-20 °C; salinity of 30-35 g/L) and fed on a high protein diet (CP 50-55%) and low fat (8-10%), it reaches the commercial size (350 g) after 16-18 months (Colen et al., 2014). CS can tolerate a wide range of rearing temperature (18-24 °C), without compromising growth performances, survival, FCR and plasma cortisol levels (Tibaldi et al., 2007). Moreover, CS requires a higher lipid diet content between 18 and 21% (Parisi et al., 2014). According to Kals et al. (2017), CS fed with a commercial diet suffered from anaemia and it was observed that a diet based on ragworm (polychaetes) alleviated this negative effect (Kals et al., 2017). CS and SS show a successful adaptation to low-salinity environments. In detail, SS can easily and quickly (14-17 days) adapt their osmoregulatory response from low-salinity (5 g/l) to high-salinity (55 g/l) environment (Arjona et al., 2007), while CS demonstrate a better adaptation to low-salinity (15 g/l) than SS, provided the gastric evacuation rate is evaluated (Vinagre et al., 2007).

Common octopus (CO) possesses many characteristics for being considered a candidate species for aquaculture diversification: easy adaptation to captivity conditions, short life cycle (12-18 months), high growth rates (up to 13% of BW/day), high FCR (15-43%), good acceptability of frozen food, high reproductive rate, and high market price (Iglesias et al., 2000; Vaz-Pires et al., 2004). CO is a benthic, neritic species found from the coastline to the outer edge of the continental shelf (Vaz-Pires et al., 2004; Vidal et al., 2014). CO is a poikilotherm and as such, their metabolism accelerates as temperatures rise, but a cooler water temperature promotes longevity (Forsythe et al., 2001). The European climate is the perfect fit for such conditions as the optimal temperature in Europe is 10-20 °C with the maximum being 23 °C (Vidal et al., 2014). CO is stenohaline and shows very low tolerance to low salinity, with an optimal level ranging between 27 and 38 g/L (Boletzky and Hanlon, 1983; Vidal et al., 2014). The optimal conditions for octopus production should be 13-20 °C water temperature and 32-35 g/L salinity (Iglesias et al., 2000). Lipids are important nutrients for cephalopods, not only as a main source of energy but also for metabolic reasons regarding PUFAs and EPA, notably (Vidal et al., 2014). The paralarvae were successfully produced under captivity conditions, but their survival rate particularly is still considered the main bottleneck for CO production, due to lack of knowledge about their nutritional aspects (De Wolf et al., 2011; Vidal et al., 2014). A mixture of live prey (*Artemia* at different stages of life and rotifers) in combination with micro-algae (*Nannochloropsis*, *Isochrysis, Chlorella*), seemed to be a good solution for improving paralarvae survival rate (De Wolf et al., 2011; Iglesias et al., 2004). After the paralarvae stage, subadults can reach a wet weight ranging from 0.5 to 0.6 kg at 6 months and 1.4 to 1.8 kg after 8 months (Iglesias et al., 2004). Artificial feeds based on crustaceans (at least 30%), fish and squid, resulted to promote the highest growth rates (Vidal et al., 2014). Fishermen grow out CO subadults of 0.8–1.0 kg up to 2.5–3.0 kg in a period of 3–4 months at temperatures of 12–19 °C with 80% survival (Vidal et al., 2014). Production of CO in Europe was recorded just for Spain and it reaches 1.73 tonnes approximately (EU, 2019).

3.3 DEXi analysis

The results of the DEXi_SIMTAP_Fish_1.0 model showed that the candidate species were classified into 4 out of 5 scale values: GSB and ESB as 'Excellent'; FGM, SD, ME, TU and SO as 'Good'; SSB and GA as 'Medium'; CO and ST as 'Poor'.

The evaluation relevance of the model structure carried out using the 'plus/minus-1' analysis tool showed that four criteria or indicator had a larger influence than others on the root criterion score (Table 3). In detail, a theoretical variation of the value assigned to the 'hatcheries availability' (indicator of 'Domestication'), for 9 species out of the 11 candidates might determine a variation of the root criteria score (e.g. Good rather than Excellent in GSB and ESB). The same evaluation was done for all the other criteria and indicators and it was observed that 'raw products' (indicator of 'market value') was sensitive 8 out of 11 times, 'salinity' and 'temperature' (indicators of 'Environment') and 'Growth performances' 6 out of 11 times. On the contrary, the following criteria showed a limited relevance in the selection process: 'Know-how' (indicator of 'Domestication') 3 out of 11, 'Feeding behaviour' and 'Commercial diets' (indicators of 'Feeding regime') 3 out of 11 times; 'Geo-distribution' 2 out of 11 times; 'By-products" (indicator of 'Market') 1 out of 11.

4. Discussion

In this work, the SWOT analysis was used to identify the species-related features most relevant for addressing the choice of the species to be used for SIMTAP production in the Mediterranean context. The features selected by the panel of experts were in line with those suggested by Barrington et al. (2009) when a new IMTA production is launched. The SWOT analysis has already been used for addressing other relevant issues in the Aquaculture field (Bolton et al., 2009; Garza-Gil et al., 2009; Gasco et al., 2020; Rimmer et al., 2013), despite it does not allow an analytical and strictly objective evaluation of the considered single factors (Kajanus et al., 2012; Shinno et al., 2006). To this regard, the MCDM approach enhances the objectivity of the decision process. In particular, using the DEXi, the sensitivity analysis was performed in order to assess the relevance of the model structure and to estimate the accuracy of the decision process. This analysis investigates the effects on the aggregated criteria of changing the value of each indicator by one qualitative value down or up, independently of other indicators or not aggregated criteria (Bohanec et al., 2013). In general, a model is more sensitive to changes if its structure is simple and focused on the main criteria (Craheix et al., 2015). In accordance, the DEXi_SIMTAP_Fish_1.0 model indeed showed high sensitivity. For instance, even a slight change in the qualitative value assigned to low weight criteria or indicators (e.g. raw products for market value) was able to induce changes in the final result (candidates ranking).

The geo-distribution of the species or rather their natural presence in the Mediterranean area was considered as a starting point of the selection process. In fact, all the species included in this work naturally live in the Mediterranean Sea.

Regarding the market value criteria, GSB and ESB are consolidated species characterized by relevant market value (BMTI S.c.p.A, 2018; Parisi et al., 2014). Moreover, in Italy, the consumer demand for GSB and ESB is not nationally covered and approximately 80% of the internal market share is met through imports from other countries such as Greece and Turkey (BMTI S.c.p.A, 2018). GA, TU, SO and CO are also already consolidated species on the market, even though their farm production is quantitatively limited and obtained just in few European countries other than Italy (EU, 2019; Parisi et al., 2014). The raw products of FGM and ST are hardly appreciated by consumers and their market price is very low, however, it is worthy to highlight here that the production of processed by-product such as salted mullet roe and caviar (Koutrakis, 2016; Parisi et al., 2014) may represent a great opportunity for SIMTAP production.

The above-mentioned features had a limited influence on the species selection process. In fact, under the ‘geo-distribution’ perspective, all the candidates shared similar features and hence, this attribute did not make a relevant difference. The SIMTAP project is at its initial stages, and the focus is on the implementation of the system itself under a structural and biological point of view, and not, in this phase at least, on its commercial development, therefore the market acceptance of the species was considered less influential.

Despite the limited overall weight of the ‘raw products’ aggregated criterion, the relatively high sensitivity of the model to the ‘raw products’ indicator may depend on the closeness among all the candidate species in terms of the final score. In fact, to this regard, even small variations induced relevant changes in the final candidates’ ranking. On the other hand, the considered model showed reduced sensitivity to the ‘processed by-products’ indicator. This might be related to the different relevance assigned (weight): producing and selling raw products 75%, processed by-products 25% only.

The choice of suitable species to be bred within an IMTA-system should essentially match as much as possible to its environmental parameters, notably to water salinity and temperature. Considering that one of the most relevant goals of the SIMTAP EU-PRIMA project is farming marine species in combination to salt-tolerant or halophyte plants, water salinity is one of the most important parameters to be considered. In the Italy-based SIMTAP prototype, the salinity of the system should range between 20 and 35 g/L and temperature between 18 and 25 °C. For these reasons, euryhaline and eurythermal features of the candidate species were taken under high consideration. Under these perspectives, most of the considered species were adequate for the SIMTAP conditions. The stenohaline species GA and CO, as well as ST, that needs FW and low temperature, were penalized (Boletzky and Hanlon, 1983; Fernández-Palacios et al., 2015; Mazzola et al., 2000; Papadakis et al., 2008; Parisi et al., 2014; Vaz-Pires et al., 2004; Vidal et al., 2014). The considered model showed high sensitivity to these indicators, reflecting the weights assigned by the panel of experts.

Due to the high relevance of the sustainability issues within the SIMTAP idea, the feeding regime was highly considered by the panel of experts and split into two different aspects: the ‘wild feeding behaviour’ and the ‘nutritional knowledge’ so far available, the latter to ensure a successful rearing activity. In detail, the adaptability of the species to be fed on different sources in addition to their natural attitude (carnivorous or omnivorous) was thoroughly analyzed. Hence, on one hand, species strictly fed on FM and FO should theoretically be avoided while, on the other hand, the fact that they are the ones most appreciated by the consumers and already represent the main

Mediterranean aquaculture products, cannot be totally neglected. To overcome this gap, the SIMTAP idea takes under consideration the use of self-produced marine detritivores and filter-feeder organisms such as echinoderms, polychaetes and mussels, for replacing FM and FO.

Hence, with reference to ‘wild feeding behaviour’, worthy to be mentioned is FGM, which can feed on a wide variety of substrates (omnivores) and therefore, it seems one of the favourite species for SIMTAP sustainable production (Bagni, 2005c; Cardona, 2016; Vallainc, 2016). Similarly, also SSB possesses a highly flexible feeding regime, thanks to its omnivorous attitude (Cataudella and Bronzi, 2001; Favaloro et al., 2002; Parisi et al., 2014). SO naturally feed on polychaetes and other benthic organisms (Colen et al., 2014). Moreover, Kals et al. (2017) suggested how the use of ragworm-extract (*Nereis virens* Sars) in adult SO alleviates the anaemia and positively affected the SO metabolic performance (feed intake, feed efficiency and growth).

Thanks to the ‘nutritional knowledge’ and fish nutritional physiology, other carnivorous species such as ESB, GSB, SSB, ST and ME are nowadays successfully fed on more sustainable commercial feeds than in the past, largely based on plant products and by-products. Moreover, all the candidate species considered in the present study are carnivores or omnivores and theoretically suitable to be reared in the SIMTAP. Exceptions are represented by TU since its diet is still mainly based (60%) on fish raw material (Parisi et al., 2014; Ruyet and Baudin-Laurenc, 1991), and GA and CO whose optimal feeding regime is not yet sufficiently studied and undisclosed. The lack of knowledge about nutritional aspects is considered an important bottleneck to obtain significant aquaculture and SIMTAP production, notably. The ‘Low’ value of the ‘nutritional knowledge’ indicator assigned by the panel of experts to FGM, was related to the extensive rearing technique still used for this species. FGM nutrition is still largely based on the exploitation of the natural food web of lagoons (Crosetti, 2016) and too limited scientific knowledge is available about the nutritional requirement of FGM. As a consequence, no technically advanced commercial feeds are still available for this species. The adaptability of the species to feed on different sources under captivity conditions were considered more important than their feeding behaviour in the wild, even though the wild feeding behaviour remains the starting point to study new diets. In this case, the 'plus-minus-1' analysis was balanced among these two indicators, reflecting their relative weights.

Another important aspect (criterion) taken under consideration by the panel of experts was the ‘Domestication’, meaning the availability of hatcheries for juvenile supplying and farming know-how. The territorial distribution and availability of hatcheries were considered as strengths since it may facilitate the juvenile supply for SIMTAP production and favourable juvenile market price. Under this perspective, GSB and ESB juveniles are largely available on the Mediterranean and notably in the Italian market (Moretti et al., 1999; Parisi et al., 2014). The reproduction of FGM requires hormonal treatments that increase the running costs, and therefore, the hatchery production of FGM juveniles has never reached a significant commercial scale (Cataudella and Bronzi, 2001; Saleh, 2008; Vallainc, 2016). The other species suffer other limits such as the re-creation of optimal environmental conditions within the hatcheries (e.g. tanks sizes and shapes), the need of hormonal treatments to induce spawning and the lack of well-known and developed farming techniques. Nowadays, hatcheries production of SSB, GA, SD, ME and TU is absent or very limited to the country different than Italy, such as Spain for ME and TU (EU, 2019). The farming know-how was also considered as a relevant indicator. Under this perspective, GSB and ESB are the most reared fish in the Mediterranean area and the farming know-how and domestication level have already reached very high standards. In contrast, species such as GA and CO are not largely reared yet due to several bottlenecks in their farming process. GSB and ESB were the species that better fit to SIMTAP production according to this criterion. FGM, SSB, SD and ME juveniles face some difficulties in the farming and reproduction techniques, with hatcheries’ production that hasn’t reached a significant commercial scale so far (Boglione et al., 2003; Cataudella and Bronzi, 2001; Monfort, 2010; Papadaki et al., 2008; Parisi et al., 2014; Piccolo et al., 2008; Saleh, 2008; Vallainc, 2016). In this case, also, the sensitivity of the model with respect to these indicators reflects the weight assigned by the panel of experts.

Regarding the growth performances of the candidate species, fast grower species such as FGM, GA, SD, and ME, as well as CO, resulted to be the most suitable candidates for SIMTAP production (Grigorakis, 2017; Henry and Fountoulaki, 2014; Jerez Herrera and Vassallo Agius, 2016; Saleh, 2008). TU growth performances were also relevant, while GSB and ESB are not fast grower species and under this perspective were not considered positive for SIMTAP production. In this initial stage of the SIMTAP project, maximizing the biomass production (as well as its value) in every trophic level is considered the main goal. The DEXi_SIMTAP_Fish_1.0 model showed relatively high sensitivity to this criterion. Summarizing all the above-discussed issues, GSB and ESB seemed to be the most suitable fish species to be reared in the SIMTAP system, even though FGM, SD, ME, TU and SO, represented valid alternatives. According to the size of the system, it should be possible to contemporaneously rear more than one species, in separate tanks or polyculture. At this very early stage of the present project, only one species per time will be reared (GSB monoculture), while polyculture will be considered (e.g. GSB and ESB), since, this technique, might increase the technical and economical resilience of the system.

The DEXi_SIMTAP_Fish_1.0 model was implemented as DSS for a land-based prototype in the Mediterranean area with very peculiar environmental characteristics and constraints. Nevertheless, the model has provided a holistic evaluation of the considered species, increasing the objectivity in the decision process. The same method is being applied in the selection process of the other organisms of the SIMTAP system, such as plants and other extractive organisms. Similarly, the model might be adjusted and applied to other countries/zones with different environmental and/market constraints.

Craheix et al. (2015) suggested the evaluation relevance of the model outputs as a last step of the DEXi approach. This evaluation is based on ex-post assessments that due to the initial stage of the SIMTAP project it is not yet available.

5. Conclusions

The method used for identifying the species most suitable for SIMTAP production was based on a balanced combination of both subjective and objective evaluation. While the MCDM tools are not new for selecting candidate species in the aquaculture field, on the contrary, the DEXi method has never been applied so far to this purpose.

The decision process carried out using this method, consisted of several steps. After a comprehensive literature analysis of the biological, zootechnical and commercial features related to species commonly reared and spread in the Mediterranean area, a specifically selected panel of experts performed the SWOT analysis method to summarize strengthens, weaknesses, opportunities, and threats of the considered species. Then, the biological and physical constraints of the SIMTAP prototype and the criteria relevant to address the decision process were evaluated. Such criteria were identified in ‘geo-distribution’, ‘domestication’ (including ‘know-how’ and ‘hatchery availability’), ‘environmental needs’ (including ‘salinity’ and ‘temperature’), ‘feeding regime’ (including ‘wild feeding behaviour’ and ‘nutritional knowledge’), ‘growth performances’ and ‘market value’ (including ‘raw products’ and ‘processed by-products’).

With all the necessary information collected, the DEXi decision-making method was used to organized hierarchically each decision alternative, define weights and decision rules in order to obtain a final ranking of the candidate species. DEXi clearly showed to be a tool for objectively managing a variety of parameter and values, suggesting the use of this DSS for the selection of other organisms to be included in the SIMTAP ”ecosystem”.

The final output of the decision process showed that ESB and GSB (‘excellent’) were the most suitable candidates to be reared within the SIMTAP system. Strengths of these species were the ‘Domestication’ level already reached, as well as the ‘market value’. These findings do not mean that other candidate species cannot be considered for SIMTAP production or other IMTA system. In fact, FGM, SD, ME, TU or SO, were demonstrated to be ‘good’ species for these type of production systems. Moreover, worthy to be mentioned here is the case of FGM that represents an interesting alternative to GSB and ESB within the perspective to promote aquaculture diversification. This species showed such important and relevant strengths, the potential to produce both raw as well as valuable processed by-products (salted mullet roe, also known as ‘bottarga’).

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Figure

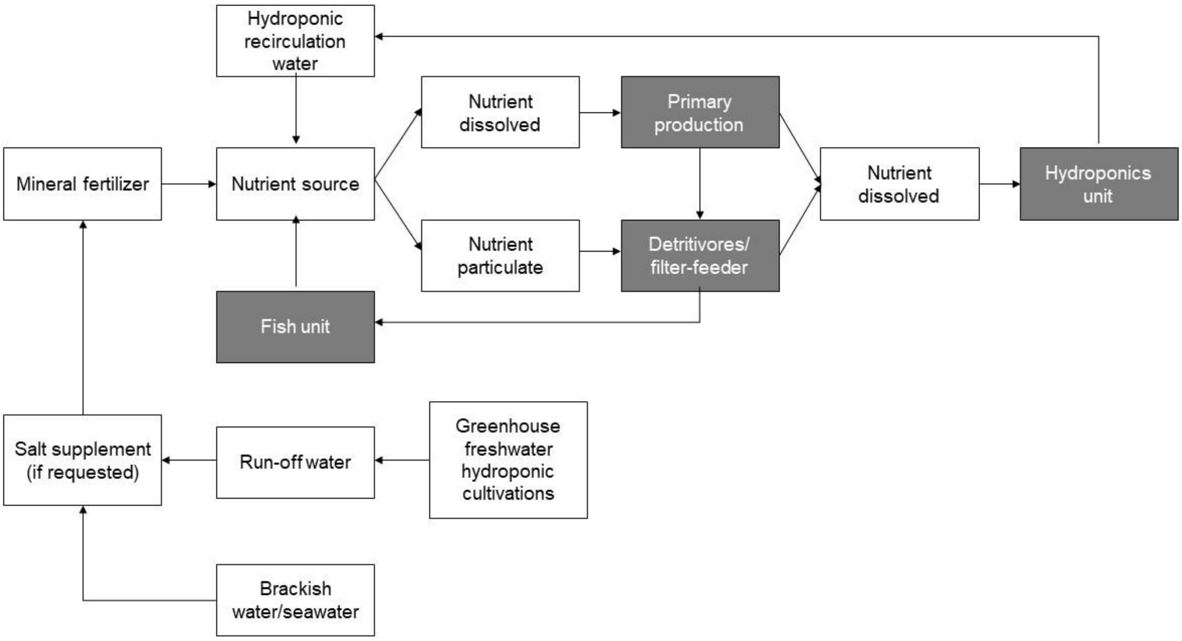

Fig. 1. SIMTAP conceptual framework. The grey boxes represent the ‘physical’ unit of the system, the white boxes represent the SIMTAP fluxes, mainly water and nutrient.

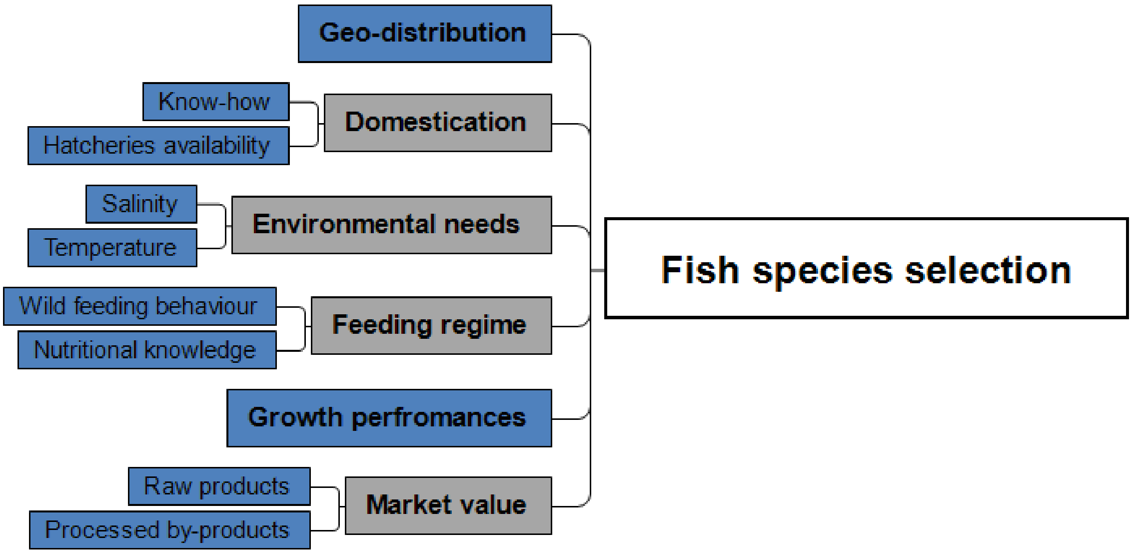

Fig. 2. Tree of attributes. Boxes with bolded letter represent criteria; blue boxes represent indicators or not-aggregated criteria; grey boxes represent aggregated criteria; white box represents the root criterion.

Table

Strength	Weaknesses
– Wide range of tolerated salinity and temperature levels of some species, – High domestication level of some species which can be easily adapt to SIMTAP environment, – Wide distribution of hatcheries and farm, – Perceivable market value for fresh or related products, – Adaptation (or low sensitivity) to a different source of feed, – High growth performances under captivity conditions,	– Very reduced euryhaline or eurythermal attitude, – Low domestication level of some species which can be easily adapt to SIMTAP environment, – Scarce or null distribution of hatcheries and farm, – Scarce acceptance from consumers, – Scarce adaptation (or high sensitivity) to a different source of feed – Poor growth performances under captivity conditions,
Opportunities	**Threats**
– Develop some “local-based” systems, according to the features and the needs of each area, – Develop some market niches for SIMTAP products related to their sustainable features, – Develop a market share for “unconventional” species,	– Economic sustainability of production, – Highly competitive market, – Availability of juveniles and/or high market price, – Products refusion by the market,

Table 1 SWOT analysis for selecting attributes

Criteria & Indicators	Description	Evaluation scale
Geo-distribution	Wild distribution in the Mediterranean Sea	Low; High
Domestication	Domestication degree of the selecting species as a combination of know-how in farming and hatcheries availability	Low; Medium; High
└ Know-how	Know-how in farming (e.g. feeding, density, requirements, etc), and developing level of culture	Low; High
└ Hatcheries availability	Distribution of hatcheries in the Mediterranean area as an indicator of juveniles availability	Low; High
Environmental needs	Environmental adaptability of the selected species	Low; Medium; High
└ Salinity	Tolerance of wide range of salinity	Low; High
└ Temperature	Tolerance of wide range of temperature	Low; High
Feeding regime	Feeding adaptability of the species	Low; Medium; High
└ Wild feeding behaviour	Wild feeding behaviour of the selected species	Low; High
└ Nutritional knowledge	Know-how nutrition and feeding formulation of the selected species (e.g. alternatives raw materials inclusion)	Low; High
Growth performances	Growth speed of the selected species	Low; High
Market value	Market acceptance by consumers	Low; Medium; High
└ Raw products	Consumer acceptance of fresh products (whole fish)	Low; High
└ Processed by-products	Consumer acceptance of processed by-products (e.g. bottarga and caviar)	Low; High
Fish species selection	Selecting the most suitable fish species for SIMTAP (Italy)	Unacceptable; Poor; Medium; Good; Excellent

Legend: Grey highlighted rows indicates criteria

Table 2 Tree of attributes, criteria description, and evaluation scale

Indicators	%	Species										
		GSB	ESB	FGM	SSB	GA	SD	ME	TU	ST	SO	CO
Geo-distribution	4	H	H	H	H	H	H	H	H*	H*	H	H
Domestication	**24**	**H**	**H**	**M**	**L**	**L**	**M**	**M**	**M**	**M**	**M**	**L**
└ Know-how	25	H	H	H*	L*	L	H	H	H*	H	H	L
└ Hatcheries availability	75	H*	H*	L	L*	L*	L*	L*	L	L*	L*	L*
Environmental needs	**24**	**H**	**H**	**H**	**H**	**M**	**H**	**H**	**H**	**L**	**H**	**L**
└ Salinity	50	H*	H*	H*	H	L*	H	H	H*	L*	H	L
└ Temperature	50	H*	H*	H*	H	H*	H	H	H*	L*	H	L
Feeding regime	**24**	**H**	**H**	**M**	**H**	**M**	**H**	**H**	**M**	**M**	**H**	**L**
└ Wild feeding behaviour	25	H	L	H*	H	H*	H	H	H*	H	H	L
└ Nutritional knowledge	75	H*	H*	L	H	L	H	H	L	H	H	L*
Growth performances	20	L	L	H*	L*	H*	H	H	L	L*	L*	H*
Market value	**5**	**H**	**H**	**M**	**L**	**H**	**L**	**L**	**H**	**M**	**H**	**H**
└ Raw products	75	H*	H*	L	L*	H	L*	L*	H*	L*	H	H*
└ Processed by-products	25	L	L	H	L	L	L	L	L	H*	L	L
Fish species selection		**Excellent**	**Excellent**	**Good**	**Medium**	**Medium**	**Good**	**Good**	**Good**	**Poor**	**Good**	**Poor**

Legend: 'GSB' Gilthead seabream; 'ESB' European seabass; 'FGM' Flathead grey mullet; 'SSB' Sharpsnut seabream; 'GA' Greater Amberjack; 'SD' Shi Drum; 'ME' Meagre; 'TU' Turbot; 'ST' Sturgeon; 'SO' Solea; 'CO' Common Octopus; 'H' High; 'M' Medium; 'L' Low; Bold letter: indicates the criterion result come from sub-indicator values; Grey highlighted rows indicates criteria; Asterisk '*' means that a 'plus-minus 1' change of the indicator's score affects the 'Final score';

Table 3 Evaluation for selected species (with % of relevance of each indicators) and sensitivity analysis for criteria, using DEXi method