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Dynamic Energy Budget provides mechanistic derived quantities to implement the ecosystem based management approach

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ABSTRACT

The on-going climate change threats are rapidly growing at both global and local scales, affecting ecosystems, societies and economies by altering natural distribution and productivity of key commercial species. Although the ecosystem based management (EBM) focuses on ecosystem equilibria, to provide realistic management measures for important activities at sea such as fisheries and aquaculture, there is a need of quantities; mechanistic approaches are suggested as reliable solutions. Here, a Dynamic Energetic Budget (DEB) application studies the link between environmental change (temperature forecasted increasing scenario in a context of COP 21 [Paris climate conference Agreement] and food density increase) and life-history traits of some Mediterranean fishery and aquaculture target species (*Engraulis encrasicolus*, *Dicentrarchus labrax*, *Mytilus galloprovincialis*, *Crassostrea gigas*). A sensitivity analysis was applied to simulate the effects of future environmental change on the time needed to reach the commercial size and the length at first maturity. We also explored the efficiency of Integrated Multitrophic Aquaculture (IMTA) as a potential management solution in a context of an adaptive EBM. The worst scenario of rising temperatures (+2 °C) seems to reduce the time needed to reach the commercial size in most species and IMTA potentiates the thermal effect on it. A spatial contextualisation of model outcomes allowed disentangling potential conflicts among human activities at sea. The DEB based life history traits approach can provides quantities to inform the management of marine activities at local scale additionally allowing translating complex results into useful figurative representations for stakeholders.

1. Introduction

Climate change represents an ongoing and rapidly growing threat at both global and local scale equally affecting the environment, societies and economies by forcing shifts in the distributional range and productivity of key commercial species (Lam et al., 2016). The magnitude of these effects on marine species (both in the wild and captive conditions) and their replies (*e.g.* increase or decline of abundance; Pecl et al., 2017) can vary and the possible changes can depend on: *i)* species life-histories traits, *ii)* local environmental conditions and *iii)* contextual presence of more than one anthropogenic related stressor (Gunderson et al., 2016; Pecl et al., 2017; Sarà et al., 2018a, 2018b, 2018c). The effect of increasing temperature pushes species distribution shifts at large scales, such as the poleward shift, which seems concurrent across the current literature (Poloczanska et al., 2013; Mieszkowska et al., 2014; Rutterford et al., 2015; Sarà et al., 2018b). What is still poorly recognized and understood is how the effect of multiple drivers of environmental change vary in space and time at local scale. Additionally and contrary to what happened so far, the future management of socio-economic important activities at sea, such as fishery and aquaculture, as well as the corresponding systems of governance, should be informed by observations and predictions made at local scale. Only a more adaptive management that integrates approaches that involve the full array of interactions within an ecosystem, including humans, rather than considering single issues in isolation, starting from an appropriate knowledge of species biological traits, will allow the translation of the effects of environmental change into realistic management measures (Carpenter and Folke, 2006). Thus, strategies of dynamic adaptation should be designed taking into account new more ongoing favourable environmental conditions affecting the optimisation of the species' biological traits (Sarà et al., 2018a, 2018b, 2018c) to avoid unrealistic or inapplicable management measure. Oftentimes, this leads to measures that generate conflicts in between the different anthropogenic activities that foster tension among coastal stakeholders (Baudron and Fernandes, 2015; *sensu* Sarà et al., 2018a).

The Dynamic Energy Budget Theory (Kooijman, 2010) feeding the functional-based approach (Schoener, 1986; Kearney and Porter, 2009; Kooijman, 2010; Sarà et al., 2014, 2018c) may represents an effective

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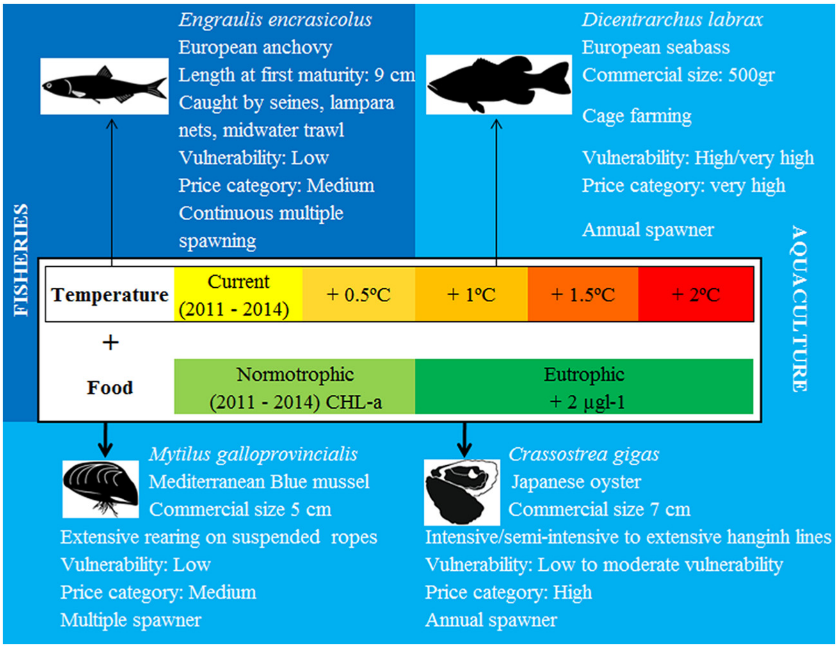

Fig. 1. Conceptual framework showing the simulated scenario of "temperature" increase (from current scenarios, years 2011–2014 to +2 °C, step 0.5 °C) and "food" increase (from a current "normotrophic" condition, 2011–2014 CHL-a, to "eutrophic" condition +2 µgl^{-1}). Variation of the commercial size, proxy of the duration of the grow-out production phase, have been modelled along a temperature and food increasing scenarios for the two bivalve aquaculture target species (*Mytilus galloprovincialis* and *Crassostrea gigas*) in order to text the Integrated Multi-Trophic Aquaculture, IMTA, effects as a potential management solution in a context of an adaptive ecosystem based approach. Variations of the commercial size of the farmed fish, *Dicentrarchus labrax*, and length at first maturity on the fisheries target species, *Engraulis encrasicolus*, have been modelled along a temperature-increasing scenario only. Notes: the +2 °C temperature increase value reflects the foreseen worst temperature increasing scenario in COP21 (Paris climate conference Agreement, 2015); the +2 µgl^{-1} food increase value (Chlorophyll-a, CHL-a) reflects an eutrophic condition simulating the trophic enrichment of a typical IMTA, condition. Data on the farming or fisheries methods, selected sizes, vulnerability, price and spawning have been reported to better characterise the selected target species (FAO CASIP, 2004http://www.fao.org/fishery/culturedspecies; https://www.fishbase.org/; http://www.sealifebase.org/).

and powerful mechanistic tool in providing those kinds of quantities to inform effective and flexible fisheries and aquaculture management plans. Spatially contextualised quantities based on functional traits of fished and cultivated species (*e.g.* Sarà et al., 2018a) can help us in disentangling the effects of increasing temperature due to climate change. Such kind of information can preserve and reinstate the socio-economic integrity of marine regions in shifting, dynamic and changing ecosystems (UNEP/MAP, 2016).

Here, we introduce a comprehensive approach that integrates quantities generated by a mechanistic DEB based application, with the aim to operationalize, inform and support a more adaptive management of marine resources and the related development (*e.g.* fisheries ad aquaculture). Our framework involves a spatially-explicit module where, by mapping our outcome, we were able to contextualise potential management issues. In this regards, Sicily, due to the cross-border central position in the Mediterranean Sea, coastal socio-economies based on sea-related products (*e.g.* seafood, oil and gas extraction) and peculiar physiography and oceanography, can represent an ideal case study area to test the effectiveness of integrated approaches and to explore possible benefits coming from a quantitative mechanistic analysis based on species traits (Mangano and Sarà, 2017; Mangano et al. 2017a, 2017b; Capodici et al., 2018). In doing so, we identified and quantified the spatio-temporal shifts under climate change in terms of time to reach both the commercial size for three selected aquaculture model species (*Mytilus galloprovincialis*, *Crassostrea gigas*, *Dicentrarchus labrax*) and the length at fist maturity for the fishery model species, *Engraulis encrasicolous* (hereafter TIME). All these species are common and highly valuable in the Mediterranean fisheries and aquaculture and are among the most consumed species in the Basin. We used the power of the functional-based approach to generate at regional level the kind of site-specific mechanistic predictions of species shifts resulting from climate change (in terms of increasing temperature from 0.5 to 2.0 °C in respect of the current worst scenario increasing temperature - *sensu* COP 21 Paris climate conference Agreement; Hulme, 2016a, 2016b). In the specific case of two out three farmed bivalves (*M. galloprovincialis* and *C. gigas*) we crossed the thermal outcomes with another potential source of variation such as the trophic enrichment (in terms of chlorophyll-a increase), simulating the presence of an Integrated Multi-Trophic Aquaculture (IMTA; Sarà et al., 2012) when more species belonging to different trophic levels are cultivated together (Sarà et al., 2012; Sarà et al., 2018a). Thus, we performed an analysis crossing both temperature increase (from current up to +2 °C) and trophic condition scenarios (normo-trophic conditions *vs.* IMTA trophic enrichment conditions).

Quantities produced by our approach were mapped allowing to spatially visualize a quantitative informational baseline of climate effects on our target species. These can be used in helping scientists to inform policy makers and stakeholders with the final aim to produce more tailored management strategies and plans based on local scale outcomes.

2. Materials and methods

The DEB model represents the "quantitative from scratch" framework which mechanistically investigates the fluxes of energy that one organism activates in order to optimize fitness during the life span (Marquet et al., 2014; Kearney et al., 2015). The mechanistic properties rely on energy and matter flows from habitat through organisms. Flows of energy and matter (and time) through habitats and organisms are subjected to conservation laws (Charnov and Krebs, 1974) and, consequently, they are traceable (and "budgetable" accountable) processes. We can use these principles to mechanistically predict the functioning of each species and thereby the magnitude and variability of life-histories traits (Loreau, 2010; Kearney, 2012; Pethybridge et al., 2013). The standard DEB model (Kooijman, 2010; Kearney, 2012) incorporates whole-organism bioenergetics, allowing the connection between the individual behaviours to population growth *via* the description of how energy and mass are managed by organisms and how metabolic trade-offs are involved in response to local environmental change. The mechanistic nature of the standard DEB model allows that the bioenergetics features of any organism may be related to environmental conditions, so that growth rate and the ultimate fitness can be predicted. This is only feasible if the organismal body temperature and food density available are known, as for our four studied target species and when all DEB parameters of that species have been estimated (Pethybridge et al., 2013). Here we selected two fishes, the European anchovy, *Engrauils encrasicolus* and the European seabass, *Dicentrarchus labrax*, and two bivalve molluscs, the Japanese oyster, *Crassostrea gigas* and the Mediterranean Blue mussel, *Mytilus galloprovincialis* (Fig. 1). Metabolic rates of these ectotherms such as all living organisms depend on body temperature and the available food density of the environment where organisms live. DEB describes the dynamics of these processes and the possibility of modelling the effects of body temperature and food density assumes an important role to predict where, when and with what magnitude species' persistence evolves over time (Montalto et al., 2014) with potential repercussions on biodiversity and local economies. The amount of energy from food available to biological processes is regulated, in the DEB theory, by Holling's functional responses (Holling, 1959). Once food is ingested, the amount of energy from food flows through the organism at some extent depending on physiological rates. Body temperature represents an important constraint in the DEB theory especially in ectotherms in which it approximates that of the mean temperature (*e.g.* seawater as in fish). The effect of temperature on metabolism follows the Arrhenius relationship (1889) (Kooijman, 2010). Arrhenius temperature and the lower and upper boundaries of the body temperature tolerance range can be extrapolated from literature data or estimated by a direct calculation of physiological rates at different temperatures (Pethybridge et al., 2013; Sarà et al., 2013a, 2013b). The DEB model allows us to quantify some of the most important life history traits (Sarà et al., 2011, 2014). For the purpose of this study, we extrapolated and presented the duration of the grow-out phase as expressed in terms of days (TIME), needed to reach the minimum "commercial size" for the three aquaculture target species and the minimum "length at first maturity" for the fisheries species. These size were gathered from literature (FAO CASIP, 2004; http://www.fao.org/fishery/culturedspecies; https://www.fishbase.org/; http://www.sealifebase.org/). In Table 1 and Fig. 1, we both reported DEB parameters for all species and a graphical description of the applied approach on the model target species.

2.1. Environmental variables to run DEB models

To study the potential overlap among activities at sea, aquaculture and fisheries, we spatially contextualised our analysis in the central Mediterranean Sea, around Sicily. Sicilian coasts provide an ideal model area to test the power of this mechanistic approach as there are many conflicts at sea to be solved and local economies strongly rely on fisheries and aquaculture products. Thus, we downloaded 4-year datasets (2011–2014) from the Environmental Marine Information System (EMIS) maintained at the European Joint Research Centre website (http://emis.jrc.ec.europa.eu/) and MyOcean (http://www.myocean.eu) of, respectively, daily chlorophyll-a (CHL-a), weekly Net Primary Production (NPP) and daily Sea Surface Temperature (current SST). These datasets were used to feed DEB models of present 4 target species under current conditions (2011–2014). Data have been downloaded with a spatial resolution of 0.11° to obtain 68 coastal pixels covering about 850 km of the Sicilian coastline. SST and CHL-a were obtained for all 68 pixels and CHL-a was used as a proxy of available food to bivalve target species as commonly carried out in the current literature and in several companion studies (*e.g.* Sarà et al., 2011, 2012, 2013b, 2014, 2018b). Instead, for the European anchovy which was the only wild fisheries species, we extrapolated a spatially continuous dataset of food density throughout the study area and across time (Strömberg et al., 2009). This method transforms the local Net Primary Production into wet mass of zooplankton (mg m^{-3}) starting from values of Carbon per Unit Volume expressed as grams of Carbon per cubic metre and after having converted it into the wet mass of zooplankton by the coefficient of conversion provided by Cushing et al. (1958). Food for anchovy was obtained only for 45 pixels due to the lack of consistent Net Primary Production data in 23 pixels out 68. For the only intensive cultivated captive species (seabass; *i.e.* not relying on natural food under wild conditions; Sarà et al., 2018a), the effect of food was expressed through calibrating the functional response using growth and environmental data coming from Sicilian farms (Sarà et al., 2018c). Thus, we adjusted the half-saturation coefficient (which is a measure of how much organism are able to adapt to local food conditions) to fit the observed fish length reached in Sicilian farms.

To simulate the future increasing temperature scenarios forecasted by COP 21 (Hulme, 2016a, 2016b), we performed a simulation study (hereafter sensitivity analysis). Thus we ran DEB models pixel by pixel and increasing the current temperature from 0.5 °C to 2.0 °C (0.5° step), we obtained 4 increasing temperature DEB scenarios (current +0.5 °C, +1.0 °C, +1.5 °C, +2.0 °C; Fig. 1). The procedure was stopped at +2.0 °C which represents the worst COP 21 scenario expected in the coming years (Hulme, 2016a, 2016b). We decided to apply this type of procedure as it is defined more reliable than using IPCC (AR4 or AR5; Montalto et al., 2016) simulations from current up to the year 2050–2075 based on the Representative Concentration Pathways, RCPs (Moss et al., 2010; Cheung et al., 2017).

One objective of this study was to explore the efficiency of IMTA as

Table 1

DEB parameters for *Mytilus galloprovincialis, Crasssostrea gigas, Dicentrarchus labrax and Engraulis encrasicolus* (1 = Kooijman, 2010, 2 = van der Meer, 2006, 3 = Sarà et al., 2011, 4 = Thomas et al., 2006; 5 = Schneider, 2008; 6 = Rico-Villa et al., 2010; 7 = Cardoso et al., 2006; 8 = Pouvreau et al., 2006; 9 = Sarà et al., 2018c; 10 = Freitas et al., 2010; 11 = Eroldoğan et al., 2004; 12 = Dalla Via et al., 1987; Claireaux and Lagardere, 1999; Person-Le Ruyet et al., 2004; Claireaux and Lefrançois, 2007; 13 = Pethybridge et al., 2013; 14 = Teal et al., 2012); * denotes parameters governing physiological rates based on experimental data at 25 °C, the others are given at the respective reference temperature.

Symbol	Description	Units	*Mytilus galloprovincialis*		*Crassostrea gigas*		*Dicentrarchus labrax*		*Engraulis encrasicolus*	
			Value	Ref	Value	Ref	Value	Ref	Value	Ref
Vb	Structural volume at birth	cm^3	0.0000013	1	0.00000015	6;7	–	–	0.000225	13
Vs	Structural volume at seeding	cm^3	–	–	–	–	4.17	9	–	–
Vp	Structural volume at puberty	cm^3	0.06	2	1.40	7	419.60	10	1.73	13
δ_M	Shape coefficient	–	0.225	–	0.175	–	0.217	10	0.169	–
$\{\dot{J}x_m\}$	Maximum surface area-specific ingestion rate	$J\,cm^{-2}\,h^{-1}$	8.2	4	23.3	7*	58.5	9	13.5	13
ae	Assimilation efficiency	–	0.88	3	0.75	8	0.89	11	0.71	13
X_K	Saturation coefficient	$\mu g\,l^{-1}$	2.1	3	9.5	8	0.034	9	33.0	13
$[E_G]$	Volume-specific cost of growth	$J\ cm^3$	5993	5	1900	6	5600	10	4000	13
$[E_m]$	Maximum storage density	$J\ cm^3$	2190	2	2295	6	3850	10	2700	13
$[\dot{p}_M]$	Volume-specific maintenance cost	$J\,cm^{-3}\,h^{-1}$	1	2	24	6*	1.71	10	2	13
κ	Fraction of utilized energy spent on maintenance and growth	–	0.7	2	0.8	free fit	0.8	9	0.7	13
κ_R	Reproduction efficiency	–	0.8	3	0.7	8	0.95	12	0.95	13
T_A	Arrhenius temperature	°K	7022	–	5800	–	6228	12	9800	–
T_L	Lower boundary of tolerance range	°K	275	2	281	6	279	12	278	14
T_H	Upper boundary of tolerance range	°K	296	2	305	6	303	12	305	14
T_{AL}	Rate of decrease at lower boundary	°K	45430	2	75000	6	7333	12	50000	14
T_{AH}	Rate of decrease at upper boundary	°K	31376	2	30000	6	3961	12	100000	14

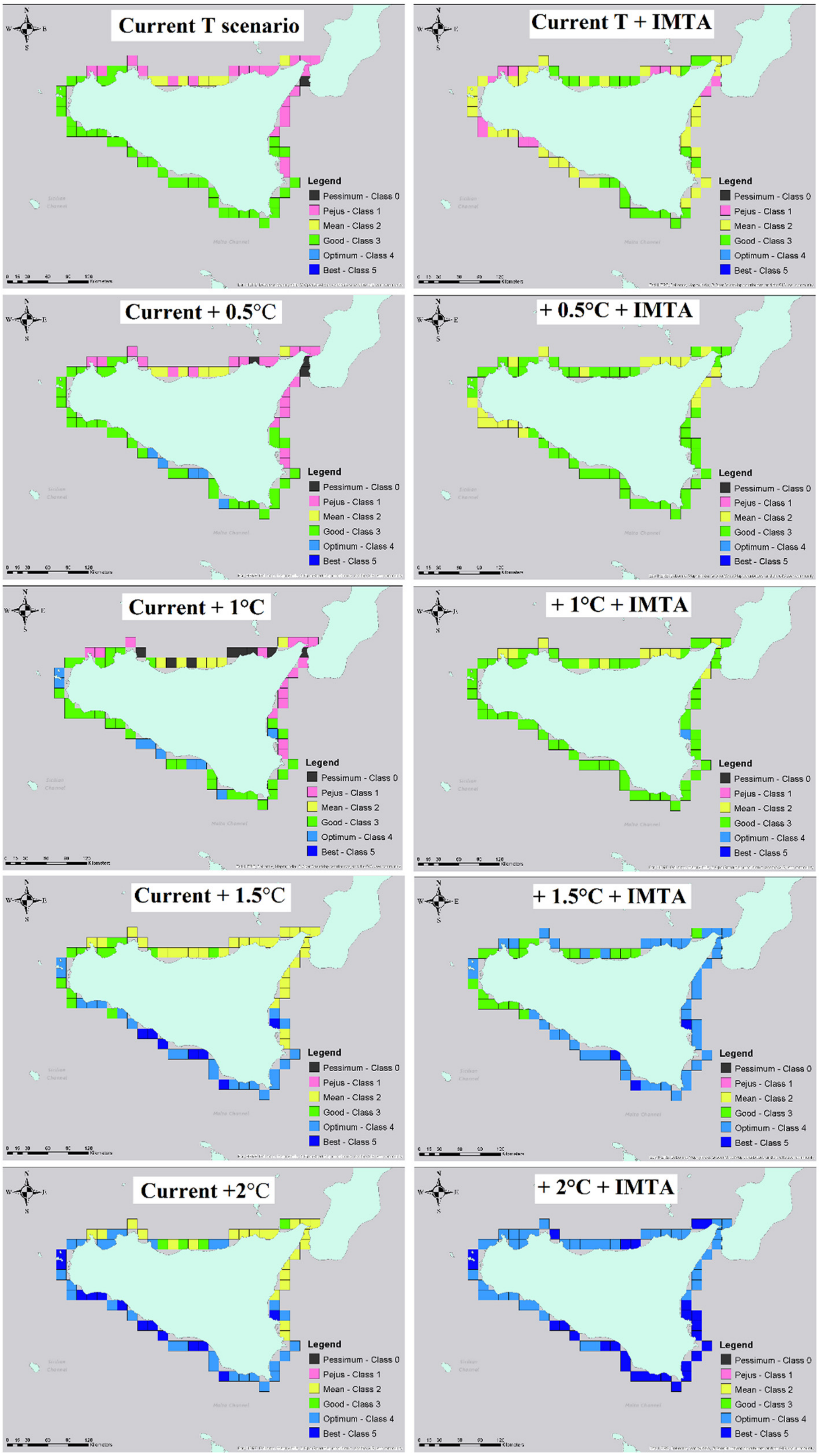

Fig. 2. Aquaculture target species – *D. labrax*, *C. gigas* and *M. galloprovincialis* – maps showing the percentile class in which each pixel around Sicily falls. On the left panel of each rows the mapped outcome obtained by cultivating species separately; on the right panel the mapped outcome obtained when species were combined in IMTA. From top to bottom mapped outcome under increasing temperature conditions from current up to current +2 °C (step 0.5 °C; the first panel of each column is the current, the last panel current +2 °C). Black = “Pessimum” condition (Class 0, 97.5% percentile, *i.e.* μ + 2σ); Pink = “Pejus” condition (Class 1, 84.1% percentile, *i.e.* μ + 1σ); Yellow = “Mean” condition (Class 2, 50% percentile, *i.e.* μ); Green = “Good” condition (Class 3, 15% percentile, *i.e.* μ-1σ); Light blue = “Optimal” condition (Class 4, 2.5% percentile, *i.e.* μ-2σ); Blue = “Best” condition (Class 5, 0.1% percentile, *i.e.* μ-3σ). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a potential management solution in a context of an adaptive ecosystem based approach. Thus, we ran pixel by pixel models for bivalves both under current “normotrophic” conditions – as expressed by current CHL-a data (2011–2014) – and under “eutrophic” conditions as expressed by a CHL-a increment of 2.0 $\mu g\,l^{-1}$ (according to Sarà et al., 2012 observations of the fish culture trophic aided-enrichment on *Crassotrea gigas* and *Mytilus galloprovincialis* life-histories traits; Gulf of Castellamamre, Sicily).

In total, we ran 1925 simulations and data have been presented through percentile maps in the attempt to express the model outcome

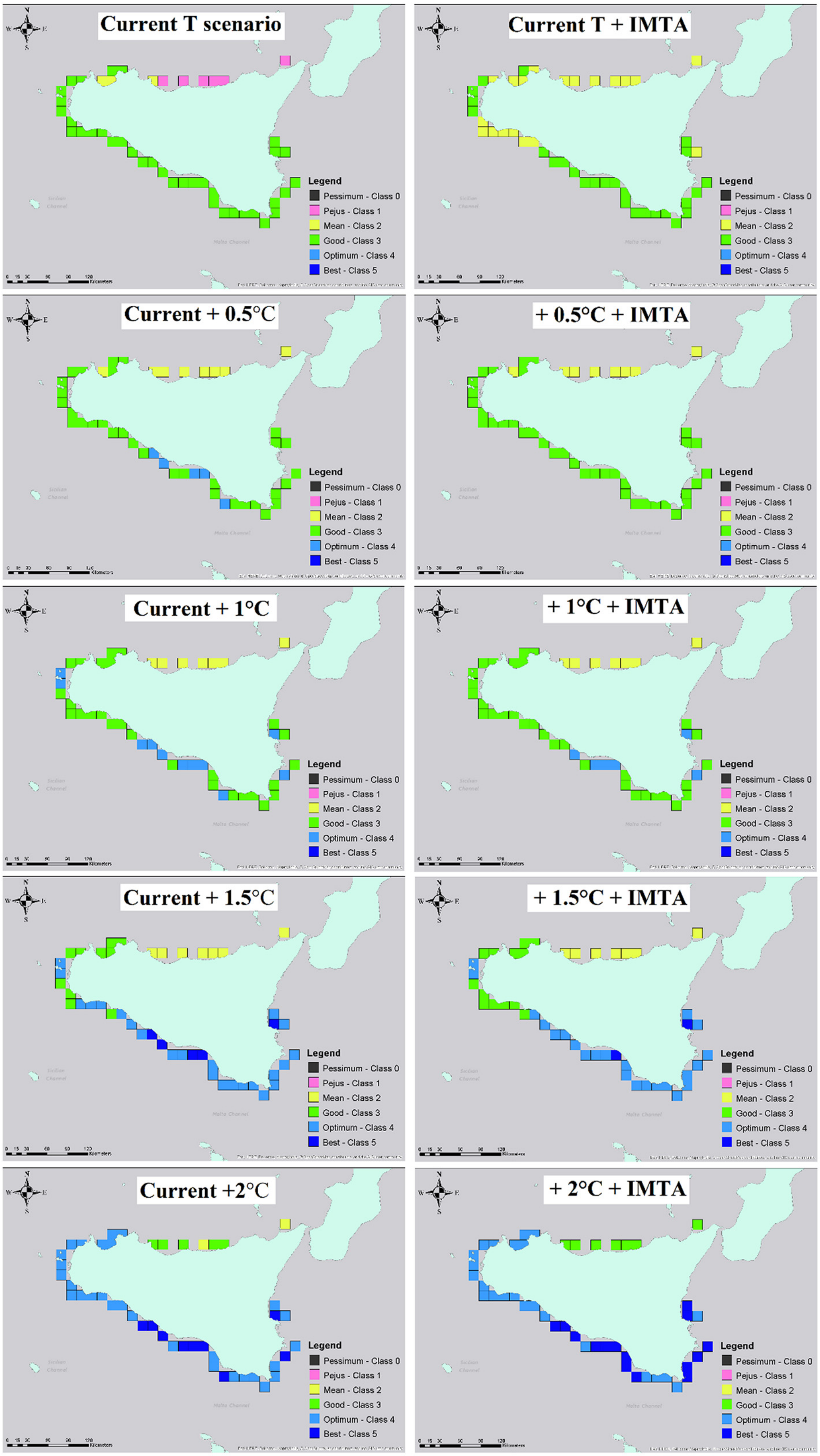

Fig. 3. Maps showing the percentile class in which each pixel around Sicily falls when combining fishery and aquaculture target species. On the left panel of each rows the mapped outcome obtained by cultivating species separately; on the right panel the mapped outcome obtained when species were combined in IMTA. From top to bottom mapped outcome under increasing temperature conditions from current up to current +2 °C (step 0.5 °C; the first panel of each column is the current, the last panel current +2 °C). Black = "Pessimum" condition (Class 0, 97.5% percentile, *i.e.* μ + 2σ); Pink = "Pejus" condition (Class 1, 84.1% percentile, *i.e.* μ + 1σ); Yellow = "Mean" condition (Class 2, 50% percentile, *i.e.* μ); Green = "Good" condition (Class 3, 15% percentile, *i.e.* μ-1σ); Light blue = "Optimal" condition (Class 4, 2.5% percentile, *i.e.* μ-2σ); Blue = "Best" condition (Class 5, 0.1% percentile, *i.e.* μ-3σ). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

through a synthetic indicator (Figs. 2-3). We subsequently calculated the overall mean TIME for each species, defined by averaging the TIME values of all pixels and we grouped 6 classes of percentiles in order to study the temporal deviation of every pixel in respect to the overall mean. Class 0 = 97.5% percentile (*i.e.* μ + 2σ) represented the "Pessimum" condition (black pixels); Class 1 = 84.1% percentile (*i.e.* μ + 1σ) represented the "Pejus" condition (pink pixels); Class 2 = 50% percentile (*i.e.* μ) represented the "Mean" condition (yellow pixels); Class 3 = 15% percentile (*i.e.* μ-1σ) represented the "Good" condition (green pixels); Class 4 = 2.5% percentile (*i.e.* μ-2σ) represented the "Optimal" condition (light blue pixels) and Class 5 = 0.1% percentile (*i.e.* μ-3σ) represented the "Best" condition (blue pixels) (Figs. 2, 3). In so doing, we classified all pixels and we made all species comparable. This kind of analysis would show, for instance, that if one pixel of a certain target species fall into Class 0, the environmental conditions supporting growth are the worst and the time to reach the commercial size is the greatest. At the other extreme, if a pixel fall into Class 5, the time needed to reach the commercial size is the shortest in respect to the mean and so on.

3. Results

All DEB models generated outcomes which were in line with already observed data and we are therefore confident that our analysis generated realistic results (see Sarà and Mazzola, 1997; Sarà et al., 1998; Sarà et al., 2018a, 2018b; Sarà et al., 2012 for *M. galloprovincialis* and *C. gigas* model validation; Sarà et al., 2018c for *D. labrax;* Basilone et al., 2006 for *Engrauils encrasicolus*).

Overall, the increasing temperature from current up to +2 °C generated conditions for reducing the time to reach the commercial size in most species of this study. Seabass was the only species that underwent a fluctuating behaviour, in that TIME reduced up to +1.0 °C (*i.e.* 679 days) and later started to increase again reaching 710 days on average in all 68 Sicilian pixels. Bivalves, when not cultivated under IMTA conditions and then separately in respect to fish farms, reduced their TIME of about 4% and 6% (Table 2), for *Mytilus* and *Crassostrea*, respectively. However, if both bivalves are cultivated under IMTA enriched conditions, as those commonly measured close to the European fish farms, the trophic enrichment generated a sort of synergistic acceleration of TIME of at least 2–3% more than normo-trophic conditions (no IMTA). While aquaculture species benefited from increasing temperature, to a certain extent, within 10%, TIME values of the European anchovy decrease to almost 20% (17.8%, Table 2) in respect to the current; this translates into a temporal anticipation of reaching the puberty size of almost two months (49 days fewer than current). The spatial contextualization of what we observed at single level species follows the same line: the warmer the temperature, the faster the growth. Thus, as shown in Fig. 2, it is easy to observe that when the temperature increases, aquaculture species not cultivated together (Fig. 1), reach the commercial size before current, with some exceptions when temperature was +1 °C (black pixels in the northern area). This spatial pattern becomes more robust when species are combined in IMTA, in that the trophic enrichment seems to potentiate the effect of increasing temperature on TIME. Consequently, under a COP21 worst case scenario and under IMTA conditions, many Northern Sicilian pixels change their TIME and all fall into Class 4 and 5 (*i.e.* the TIME is smaller than 2 and 3 standard deviation units in respect to the mean, meaning that the species grow much faster). In Fig. 3, the reported maps also combine fishery (*Engraulis encrasicolous*) pixels. Unfortunately, due to lack of NPP data, we can show only 45 pixels out 68 but this is sufficient for the purpose of this study, as it shows that increasing temperature affects the spatial suitability of most areas around Sicily. Specifically, under the worst case COP 21 scenario, only some northern areas will be less suitable for both activities, both with and without IMTA.

Table 2

a) The estimated time to reach the commercial size (TIME) for the whole study area in all scenarios and b) the percentage difference between TIME under current conditions and other scenarios.

a) TIME	Current	Current +0.5°	Current +1.0°	Current +1.5°	Current +2.0°
Engraulis encrasicolous	273	260	247	235	224
Dicentrarchus labrax	700	685	679	685	710
Mytilus galloprovincialis	967	957	947	938	929
Crassostrea gigas	1135	1114	1098	1082	1068
M. galloprovincialis IMTA	538	529	519	509	498
C. gigas IMTA	205	201	197	193	188
b) TIME Diff%	Current	Current +0.5°	Current +1.0°	Current +1.5°	Current +2.0°
Engraulis encrasicolous	–	4.7	9.3	13.7	17.8
Dicentrarchus labrax	–	2.2	3.0	2.2	−1.4
Mytilus galloprovincialis	–	1.1	2.1	3.0	3.9
Crassostrea gigas	–	1.9	3.3	4.7	5.9
M. galloprovincialis IMTA	–	1.8	3.6	5.5	7.4
C. gigas IMTA	–	2.1	4.1	6.1	8.2

4. Discussion

Our integrated experimental and modelling approach shows that the increasing temperature within the current thermal species-specific boundaries of present target organisms will cause a general shortening of both cultivation time and length at first maturity (TIME) with an effect which was variable among present target species. The fisheries species will be subjected to a larger reduction, up to two months (about 20% under the scenario +2 °C) in the time to reach the puberty size, while the effect of increasing temperature on the aquaculture species will be much smaller. While it is not the purpose of this study to comment on the potential adaptive and economic implications induced by our highlighted climate change temporal shifts, we notice that there is a growing body of research showing that climate change induces spatial shifts in terms of distributions towards the poles (Poloczanska et al., 2013), to deeper waters (Dulvy et al., 2008) or following temperature velocity (Pinsky et al., 2013). Also, current literature reports numerous cases of phenological alterations which make species more vulnerable to increasing temperature (Helmuth et al., 2014) and other climate stressors. Our analysis aims to show how a DEB functional-based approach is able to provide quantities to operationalize the management of some marine activities at local scale. Nevertheless, up to date, DEB has not applied to assess the potential role of phenotypic plasticity in pushing adaptation of species under climate change; this will be a fruitful research ground for DEB scientists, evolutionary biologists and ecologists in the near future. Moreover, we preferred to perform a sensitivity analysis which is more useful than climate projections as those provided by IPCC. While these projections are routinely applied and provide a picture of the potential availability of thermal habitats, they still involve a recognized uncertainty around climate projections and are not able to provide absolute estimates of change in biological traits or range shifts (Payne et al., 2015; Kleisner et al., 2017).

Our modelling outcomes under the current scenario agrees with the common cultivation time for European seabass at these latitudes (about 22–24 months *i.e.* from 668 to 740 days; FAO CASIP, 2004; FAO, 2014; Sarà et al., 2018c). DEB outcomes for cultured bivalves was in agreement with the reality (*e.g.* Sarà et al., 2012; FAO, 2014; Martinez et al., 2018) such as that of the European anchovy, whose predicted values fell very well within those reported in the current literature for Sicilian Channel anchovy (Basilone et al., 2006; FAO, 2014).

Our outcomes from the two bivalve aquaculture target species showed that the trophic enrichment due to IMTA potentiates the effects of increasing temperature on TIME in a synergistic combination (*sensu*Gunderson et al., 2016; Sarà et al., 2018a, 2018b, 2018c). A similar effect is not new across the current literature that shows trophic augmented status (*i.e.* the trophic enrichment due to eutrophication) can work as a buffering factor being able to reduce the detrimental effects of stressor disturbance such as sea acidification (*e.g.* Connell et al., 2017, 2018). The trophic enrichment due to the IMTA practice produces a comparable effect on our tested aquaculture target species (*M. galloprovincialis* and *C. gigas*), although it is not possible to evaluate the economic effects of the further shortening of time to reach the commercial size, it might not necessarily represent a positive outcome.

When the DEB functional-traits outcome is translated at spatial level, by a spatially-contextualised and mapped analysis, it generates easy-to-read maps which are useful to engage with the stakeholders. They can easily identify and proactively implement adaptive site-specific management strategies tailored to target species. By adopting a spatial resolution of 0.11°, which corresponds to about 13 km pixels, we are able to underline some spatial bottlenecks where both fisheries and aquaculture will be not supported by local conditions or where they can be a win-win solution and become successful drivers for local economies. Our analysis allowed to highlight as the Northern Sicilian areas will become unsuitable in the future to both aquaculture activities of *D. labrax* - our target species combined in IMTA - and for the fisheries species, *E. encrasicolus;* both are weakened by the increasing temperature (*e.g.* black pixels under current +1 °C scenario). Such an analysis can help stakeholders and decision-makers to visualize those areas to be devoted to alternative activities at sea favoring the development of other sectors rather than fisheries and aquaculture, avoiding useless conflicts. On the other hand, designing specific downscaled management measures can be easy at this or higher spatial resolutions. Nonetheless, having seen the difficulty of gathering data at a sufficient scale to feed an adaptive EBM, the objective of oceanographers and climatologists should be that of increasing the resolution of their scenarios to increase the accuracy of the local-scale tailored management measures. This should be one of the most important priorities for an adaptive EBM to be able to provide tailored management measures based on ecological functioning principles at a sufficient scale to be realistic in order to reduce future socio-economical conflicts when preserving the ecosystems. The use of mechanistic-derived quantities and high resolution spatial analysis in ecology and resource management science can help us to adopt a medical analogy: the "actual patient care should be highly individualized, and patient treatment should not be based on the results of broad-scale generalizations, without considering the patient's history, risk factors and other medications" (*literally*Helmuth et al., 2014). Thus predictions of environmental effects at local scale on biological responses should not be based on only mean conditions of environmental regimes (*e.g.* monthly, annually), but should rely on higher resolution data (at least daily). A broad-brush approach could be appropriate if high resolution data are lacking, but the present-day technology (*e.g.* satellite and remote sensing; Capodici et al., 2018) and recent scientific advancement (*e.g.* DEB theory) offer impressive improvement of the temporal and spatial resolution of many types of data needed to feed regional management strategies. Thanks to DEB, we are now able to incorporate such kind of "*patient tailored*" information needs to develop appropriate tailored marine resource management.

In conclusion, our final maps can be read as a quantitative informational baseline indicator of climate risk that can be shared and discussed by scientists, policy makers and stakeholders when producing management plans at local level under pressures of climate change. The quantitative mapping of changes in species' thermal habitats and growth performance are an easy-to-communicate-tool that allows to enlarge the common people's understanding while narrowing the science-policy communication gap and ensuring a more interactive science-policy interface (Kearney and Porter, 2009; Hickey et al., 2013; Shelton, 2014; Pacifici et al., 2015; Payne et al., 2015; Gluckman, 2016; Mangano and Sarà, 2017). Our analysis, focused on a single fishery species and one aquaculture fish, is reductive although our main aim was to show the feasibility of the approach and the effectiveness of the message. Thus, we suggest extending this mechanistic approach to other fishery and aquaculture species, exploiting the power of species-specific biological traits (*sensu* Courchamp et al., 2015). This would help generate predictions about multispecies trade-offs in space and time as well as identify winners and losers in the face of climate change (Sarà et al., 2018c). Freely available multi-species trade-off maps may represent a desirable tool to drive decision-makers, stakeholders and public opinion in developing adaptation and mitigation solutions at biologically- and ecologically-relevant spatio-temporal scales. Our DEB functional-based approach and the provided scenario-based quantitative maps, showing different simulation outcomes, can represent a tool to analyze and help narrow the field of action to be taken in place (*e.g.* Decision Support Tools; *sensu* Punt et al., 2016) and to discuss possible future activities on which to build local socio-economies (Mullon et al., 2016; Fernandes et al., 2017). This will allow the fostering of the resilience of the socio-economic environment (*i.e.* more adaptive, flexible to change) when based on marine resources that respond to rapid changes in a climate change context (Ogier et al., 2016). An adaptive management based on multiple species mechanistic quantities - according to the innovative Ecosystem-Based Fisheries Management (EBFM) - are what European coastal countries need today.

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Author's contribution

All authors contributed to development of concepts, paper content and data visualization; GS and MCM wrote the manuscript; GS provided funds, hardware and software facilities; all authors reviewed and commented on final manuscript.

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