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Predictive mechanistic bioenergetics to model habitat suitability of shellfish culture in coastal lakes

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ABSTRACT

Quantitative tools based on mechanistic modelling of functional traits able to enhance the sustainability of aquaculture and most other human activities (i.e. reducing the likelihood of detrimental impacts optimising productions), are especially important factors in the decision to site aquaculture facilities in coastal lakes, ponds and lagoons and, in the case of detrimental impact, to adopt mitigation measures. We tested the ability of mechanistic functional trait based models to predict life history traits of cultivable shellfish in shallow coastal lakes. Dynamic Energy Budget (DEB) models were run to generate spatially explicit predictions of *Mytilus galloprovincialis* life history (LH) traits (e.g. body size and fecundity). Using fortnightly data of food supply and hourly data of body temperatures, and exploiting the power of mechanistic rules, we estimated the amount of faeces ejected by a fixed quantity of organisms cultivated in two shallow Southern Mediterranean (Sicily) lakes. These differed in terms of temperature and food density, implying large differences in life history traits of mussels in the two study areas. This information could help facilitate the selection of sites where environmental conditions are more suitable for aquaculture and contextually compatible with sustainability. The validation exercise obtained by comparing the predicted and observed data was nearly consistent. Therefore, a mechanistic functional traits-based model seems able to capture the link between habitat characteristics and functional traits of organisms, delineating the fundamental portion of an ecological niche, the possibility of predicting LH traits and potential ecological applications in the management of natural coastal resources.

1. Introduction

The considerable expansion of shellfish culture (e.g. bivalves) in shallow habitats such as lagoons, ponds and coastal lakes may pose serious threats to local natural biodiversity assets due to the focal impacts exerted by large amounts of cultivated biomasses (Sarà, 2007a). Currently, such detrimental impacts are reduced by using sites for a certain period of time, and then moving shellfish facilities to another location, far removed from the original site (IUCN, 2009). Each time, however, stakeholders must decide again to where facilities should be moved, in order to optimise production and minimise the impacts of cultivation. This decision process is primarily based on ecological information and socio-economic consequences. Some decision-based methods also rely on statistic-correlative approaches (e.g. Geographic Informative Systems and integrated stat-mathematical models; Vincenzi et al., 2011; Melaku Canuet al., 2012). In correlative approaches, habitat characteristics are linked through geographical information systems (GIS) to a statistical description that implicitly captures biological processes (e.g. growth or species presence) to the extent that they are statistically associated with the predictors (Kearney and Porter, 2009). Within an aquaculture context, useful predictors can be ambient factors such as water columns and sedimentary chemical (e.g. salinity), trophic (e.g. quality and quantity of food) and physical (e.g. sedimentary texture, hydrodynamics) variables (IUCN, 2009). On this basis alone, however, stakeholders have few decision tools with which to identify the best places to start new culture initiatives, i.e. where (i) shellfish growth will be maximised and (ii) there will be a smaller likelihood of impact through biodeposits released by the cultivated shellfish.

While the application of correlative modelling tools helps increase knowledge of habitat characteristics (IUCN, 2009), potentially assignable to accommodate new farming, they do not provide

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information on functional (individual) traits of the potential cultivated organisms (Sarà et al., 2011, 2012). Detailed knowledge of species-specific characteristics for every cultivated species is crucial in enhancing our discriminative ability to make correct environmental choices (*sensu* Diaz and Cabido, 2001) whilst also increasing economic income.

In the present context, functional means all those specific traits defining species in terms of their ecological roles (Diaz and Cabido, 2001), and thereby the species identity. In ectotherms such as cultivated bivalves and fish, these traits usually include tolerance and sensitivity to environmental conditions such as physiological thermal tolerance limits (Kearney and Porter, 2009) delimiting the ability of each species to maintain its metabolic machinery (Sokolova et al., 2012), to obtain energy from food, or those behavioural (e.g. swimming behaviour, habitat use, mating system) and morphological (e.g. shape) traits (Schoener, 1986) which allow optimisation of energetic income (Krebs and Davies, 1992) and ultimate fitness (Roff, 1992). Since flows of energy and matter (and time) through habitats and organisms are subjected to Conservation Laws (Kooijman, 2010) and are traceable processes, we may use these principles to quantitatively and mechanistically predict the functioning of each species and thereby the magnitude of and variability in these traits (the so-called mechanistic trait-based approach; Kearney et al., 2010, 2012) based on eco-mechanics principles (Sarà et al., in 2014).

Thus, such an approach offers new opportunities to predict reliable estimates of life history (LH) traits of every species, including in an aquaculture context (Sarà et al., 2012). This includes the eventual commercial size and time needed to reach it, the fecundity (the number of eggs produced per gram of biomass as an estimate of hatchery potential), and the number of reproductive events per life span. The ability to predict the magnitude of these traits, the ultimate fitness of a cultivated species (Stearns, 1992) and its potential role in contributing to the bulk organic matter through faecal deposits (continually released in the surroundings) and their link in a spatially-explicit environmental context (i.e. running models using local environmental to get LH results of the target species which are contextualized in a specific geographical location; Sarà et al., 2012) is recognised as especially important for the decision-making process. This could also help increase the cost-benefit thresholds between the maximization of production and the mitigation of aquaculture impacts in coastal ecosystems (IUCN, 2009).

Fortunately, coastal and estuarine management and the application of conservation science can be assisted by functional ecology and bioenergetics, thanks to recent individual-trait-based mechanistic models based on the Dynamic Energy Budget theory (DEB; Kooijman, 2010). DEB helps to gain more complete information on possible environmental conservation strategies to be adopted in exploiting aquatic resources, as in the case of aquaculture. Recent applications have shown the high reliability of DEB approaches in many ecological contexts, mostly with ectotherms such as bivalves and fish (e.g. Pouvreau et al., 2006; Sarà et al., 2011, 2012, 2013a,b; Saraiva et al., 2011a). Bivalves acquire energy from available food and transform it into biological structures (e.g. flesh and shells) at a rate directly influenced by external temperature (Kooijman, 2010). Temperature is, as in most ectotherms, the major driver controlling and regulating metabolism and biochemical kinetics (Kooijman, 2010). The mechanistic approach based on DEB depicts temperature-dependent metabolic processes with precision, and enables us to more accurately predict the growth performance of an animal, as has been successfully demonstrated recently on land with lizards (Kearney, 2012; Kearney et al., 2012) and in marine habitats with bivalves (e.g. Pouvreau et al., 2006; Kearney et al., 2010; Sarà et al., 2011, 2012, 2013a; Saraiva et al., 2012), crustaceans and fish (e.g. Jusup et al., 2011; Pecquerie et al., 2011). Moreover, DEB seems to have a potential to predict distributions of invasive organisms (Sarà et al., 2013b) or threatened species (*sensu* Kearney, 2012), as well as a simple tool which, starting from organismal functional traits and a few mechanistic rules (Kooijman, 2010), is able to provide basal information (viz. based on species identity) about the suitability of areas potentially designated to aquaculture.

Here, we present a field and laboratory-validated, theoretical exercise conducted in eastern Sicily (Southern Mediterranean), where two brackish marine coastal lakes (Faro and Ganzirri; Fig. 1) offer a great opportunity to verify whether mechanistic models are sufficiently reliable in testing the suitability of lagoon waters for shellfish culture. We chose these habitats as a study system because large amounts of environmental data (e.g. Manganaro et al., 2009) are available for DEB modelling (i.e. water temperature and food density), and also because there has been local debate about the suitability of these lakes for shellfish culture; even though, as reported in Manganaro et al. (2009), the shellfish industry has only been banned in the Ganzirri lake since 1995, while the Faro lake is still used as enclosure of mussels from Northern Italy.

We thus tested if a functional trait-based approach referring to DEB theory is useful in mechanistically predicting life history traits of the bivalve *Mytilus galloprovincialis* in the spatially explicit context of Ganzirri and Faro lakes. In doing so, the predictions were improved by accounting for the effects of water temperature on body temperature (and metabolic rates) and local food densities. We obtained life history traits of mussels such as: (i) the habitat-specific maximum length of mussels using real data (local hourly series of water temperatures and fortnightly series of food density expressed as chlorophyll-a levels); (ii) the maturation time under two conditions; (iii) the total number of eggs produced during a life span of about 4 years, and (iv) the number of reproductive events. Lastly, exploiting the mechanistic power of DEB, we estimated (v) the quantity of faeces released by a theoretical quantity of bivalves (50 tonnes) cultivated in each lake.

2. Materials and methods

2.1. The study area

The study was carried out in two brackish coastal lakes located close to Capo Peloro (Eastern Sicily; 38° 15′ 57″ N; 15° 37′ 50″ E): Ganzirri and Faro (Fig. 1). The Ganzirri lake is larger (surface 34 ha; entire volume 9.8×10^5 m^3), and shallower (6 m maximum depth) than Faro (surface 26 ha, entire volume 2.5×10^6 m^3; about 9.0×10^5 m^3 0–5 m in depth, with a maximum depth of 30 m). The Ganzirri pond has muddy sediments, and primary production is sustained essentially by phytoplankton (Manganaro et al., 2009). Faro is a small meromictic marine lake (~26 ha), characterised by sandy-muddy bottoms seasonally covered by green algal mats, although primary production there is mainly sustained by phytoplankton. Both lakes exhibit similar fetches (Manganaro et al., 2009), are characterised by wind-driven circulation, are connected to each other by a channel and have salinity levels close to that of the sea (~33–37). Seawater entering the lakes through narrow channels plays an almost negligible role in their internal circulation and hydrodynamics (Giacobbe et al., 1996; Manganaro et al., 2009).

2.2. Water temperature and food density

An important step in this study was to place the modelling exercise in a spatially explicit environmental context. To do this, we ran DEB models with mussel body temperature (BT) and food as driving forces in the life history of mussels throughout the study area (Fig. 1). We performed DEB simulations of water temperature