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Research article

Predicting the effectiveness of oil recovery strategies in the marine polluted environment

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ABSTRACT

Many recent studies have focused their attention on the physiological stress experienced by marine organisms in measuring ecotoxicological responses. Here we suggest a new approach for investigating the effects of an anthropogenic pollutant on Life-History (LH) traits of marine organisms, to provide stakeholders and policy makers an effective tool to evaluate the best environmental recovery strategies and plans. A Dynamic Energy Budget (DEB), coupled with a biophysical model was used to predict the effects of a six-month oil spill on *Mytilus galloprovincialis'* LH traits and to test two potential recovery strategies in the central Mediterranean Sea. Oxygen consumption rates were used to check for increasing energetic maintenance costs $[\dot{p}_M]$ respectively in oil-polluted system treatments (~76.2%) and polluted systems with physical (nano-bubbles ~32.6%) or chemical treatment (dispersant ~18.4%). Our model outputs highlighted a higher growth reduction of intertidal compared to subtidal populations and contextually an effect on the reproductive output and on the maturation time of this latter. The models also enabled an estimation of the timing of the disturbance affecting both the intertidal and subtidal populations' growth and reproduction. Interestingly, results led to the identification of the chemical dispersant as being the best remediation technique in contexts of oil spill contamination.

1. Introduction

The need to investigate and predict the possible effects of anthropogenic pollutants on natural and managed ecological systems is one of the most pressing challenges facing science today. Oil spills represent one among the worst risks for marine biodiversity due to high oil container traffic (REMPEC, 2008; Portopia, 2016; Zodiatis et al., 2016) and the number of oil drilling platforms often crowding semi-enclosed seas, such as the Mediterranean basin (Mangano and Sarà, 2017). The list of unexpected oil spill accidents in the last decade is long (https://en.wikipedia.org/wiki/List_of_oil_spills) and there is a pressing urgency to deepen the potential effects on marine biota on both short (days) and mid-terms (months). Thus, studies of oil spill impact and the possible quick-intervention recovery techniques using chemical-physical compounds and/or mechanisms (*e.g.* oil skimmer, boom floating, sorbent and dispersant) on the coastal biodiversity should be encouraged in basins that harbour large biodiversity and are particularly vulnerable to unexpected extreme acute pollution events (Mangano and Sarà, 2017). Once spilled, oil often reaches and accumulates on coastal intertidal habitats (De la Huz et al., 2005), the zone between the high- and low-water marks, which is recognised worldwide as crucial in providing ecosystems goods and services (Sarà et al., 2014a) but highly threatened by human activities (Barber et al., 1995; Ansari and Ingole, 2002; Orbea et al., 2006; Xia and Boufadel, 2010). Mangroves, lagoons, salt lakes, ponds, rocky shores and pools - where the worldwide marine biodiversity concentrates (Danovaro and Pusceddu, 2007) - become potential targets as already happened in the last decade (Mexico, 2010; Philippines, 2013; Bangladesh, 2014; India, 2017). As a main consequence, investigating the potential effect of oil spills on biodiversity and the degree of recovery needed could increase our understanding of how these detrimental and extreme events can be absorbed by biota. Recovery would need to include varying strategies that use chemical-physical compounds and/or mechanism such as oil skimmer, boom floating, sorbant and dispersant methods. To disentangle the effect of oil on biodiversity is likely to be difficult because of the complexity and heterogeneity of species' responses to environmental change and the choice to perform experimental studies on sentinel organisms is historically preferred by scientists (Rice et al., 1979). Since the dawn of ecological marine scientific research, marine bivalves - and more specifically mussels - have been widely used as 'sentinel' to monitor the

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wide spectrum of pollution effects on biological responses (*e.g.* 'Mussel Watch' monitoring programs). Being habitat-forming species – HFS, mussels can be easily adopted to infer on the likelihood of associated biodiversity loss (Widdows and Donkin, 1992; Widdows et al., 1995; Salazar and Salazar, 1996; Serafim et al., 2008; Sarà et al., 2013a, 2014a). Mussels can survive in the presence of both moderate trophic enriched conditions (*i.e.* suspended chlorophyll-a concentration around $1\,\mu g\,l^{-1}$ and beyond; Sarà et al., 2011b) and high pollution levels (Halldórsson et al., 2005) buffering the human-driven biodiversity loss and recording changes in the environmental quality status of aquatic habitats at local scale (Cajaraville et al., 1996). For all these reasons, mussels have been widely used as indicators of environmental pollution (Phillips, 1976) and adopted as model organisms for physiological, genetic, toxicological and ecological studies (Smolders et al., 2003; Luedeking and Koehler, 2004; Halldórsson et al., 2007; Moore et al., 2006; Browne et al., 2008). This is also testified by the growing interest in the biological monitoring role of these sessile filter feeders, recently included in the European Marine Strategy Framework Directive (MSFD, Descriptor 9, EU 2008; Gorbi et al., 2008; Scarpato et al., 2010; Andral et al., 2011) thus recognised useful site-specific bio-indicators to meet the EU Good Environmental Status (GES). The effect of pollutants on bivalves has been frequently assessed by using the Scope for Growth (SFG) approach (Widdows and Staff, 2006; Mubiana and Blust, 2007) which allowed essentially to gain a static snapshot of the current physiological status of target organisms (Widdows et al., 1995). The success of SFG (Sobral and Widdows, 1997; Sarà et al., 2000, 2008; Widdows and Staff, 2006; Halldórsson et al., 2007; Sarà and Pusceddu, 2008; Ezgeta-Balic et al., 2011) was based on the provision of an instantaneous measure of the energy status of these key-species which was used as an indicator of the 'health' of the ecosystem (Thompson and Bayne, 1974; Widdows et al., 1995; Kearney, 2012). Nevertheless, SFG did not maximize the mechanistic power of a bioenergetic approach when assessing the bottle-necks in the energy flow from the environment to the organisms, neglecting a full translation of effects in terms of Life History (LH) traits (*e.g.* habitat body size, spawning events and Darwinian fitness; Kearney, 2012). In contrast, most recently developed bioenergetics frameworks, such as the mechanistic functional trait-based (FT) models, which rely on the Dynamic Energy Budget Theory (DEB; Kooijman, 2010; Sarà et al., 2014b), allow an easier spatially-explicit contextualisation of effects (Sarà et al., 2011a; Sarà et al., 2013a; Sarà et al., 2018a,b; Mangano et al., 2018) promising to trace new paths for future restoration strategies by predicting organismal functional traits and capturing variation across species (Pouvreau et al., 2006; Pecquerie et al., 2010; Lika et al., 2011; Sarà et al., 2011a; Kearney, 2012; Sarà et al., 2012; Sarà et al., 2013a; b; Sarà et al., 2018a,b; Mangano et al., 2018). The FT-DEB approach is based on flux of energy and mass through an organism (and not on a snapshot as in a context of the SFG approach), which is a traceable process being subject to conservation laws (Denny and Helmuth, 2009; Denny and Benedetti-Cecchi, 2012; Carrington et al., 2015). Here, an FT-DEB was spatially explicit-contextualised along the Sicilian coasts (Helmuth, 1998; Kearney et al., 2010; Sarà et al., 2011a; Sarà et al., 2012; Sarà et al., 2013a,b) in order to test the role of an acute contaminant exposure and of two recovery strategies: a commercial chemical dispersant and a nano-bubble generator (see Materials and Methods section for more details). The effects of the acute contaminant exposure and the two recovery strategies was tested on the LH traits of the blue Mediterranean mussel (*M. galloprovincialis* Lamarck, 1819), one among the most abundant filter feeders in both natural and human hard substrata (*e.g.* harbours, oil-drilling platform; Andaloro et al., 2011; Maggi et al., 2014; D'Alessandro et al., 2016; Mangano and Sarà, 2017; Mangano et al., 2017). The Sicilian waters were chosen as a target oceanographic area, which is a recognised biodiversity hotspot (Medail and Quezel, 1999) subject to high risk of accidental oil spill because it holds a central crossroad position in the Mediterranean which is the largest oil traffic route in the world (Galgani et al., 2011) and hosts the second largest oil container harbour in Europe (Augusta, Southern Sicily).

The outcomes presented and discussed are the resulting integration of an experimental and modelling study settled up to investigate the acute effect of an accidental oil spill exposure and of two possible bioremediation techniques on intertidal and subtidal mussels throughout their full life cycle. First, we compared the effects of an acute (48h) hypothetical oil spill along with that of an oil spill plus two potential recovery treatments on the mussels' energetic maintenance costs (as expressed in the DEB by $[\dot{p}_M]$ parameter and estimated as a metabolic extra-cost as measured by the oxygen consumption) and then measured the effect at individual level. Subsequently we introduced the measured effect by tweaking the $[\dot{p}_M]$ parameter in an explicit contextualised DEB model to investigate the potential implications in terms of *i)* maximum total shell length; *ii)* maximum wet weight; *iii)* reproductive outputs as expressed by the number of eggs produced; *iv)* time to reach sexual maturity; *v)* timing of disturbance.

Insights from the testing of the proposed remediation measures might inform policy makers and environmental technicians when assessing the best remediation techniques that would allow a quick recovery when a benthic population might be subjected to unexpected and acute pollution effects.

2. Materials and methods

2.1. Sampling and acclimation

Specimens of *Mytilus galloprovincialis* of commercial size (mean shell length = 65.7 ± 3.8 mm) were collected in late September 2017 from an aquaculture plant located in Lake Faro (38° 15′ 59.95″ N; 15° 38′ 19.56″ E), on the north-eastern point of Sicily (Messina, Italy). As previously described elsewhere (Cappello et al., 2011), Gas Chromatography–Flame Ionization Detection (GC-FID) analysis was used to reveal the presence of chemicals in lake water (data not shown). Mussels were collected by hand and transported within 30 min to the Mesocosm Facility of IAMC-CNR of Messina (Italy; Cappello and Yakimov, 2010). The mussels were carefully cleaned and placed in a 200 l aquarium filled with natural seawater at room temperature (18–20 °C) with a field salinity (37–38‰), and fed *ad libitum* with cultured *Isochrysis galbana*. According to common experimental procedures successfully adopted in studying the bioenergetics of bivalves (Sarà et al., 2008; Ezgeta-Balic et al., 2011), the mussels were acclimated for two weeks to reduce stress generated by manipulation and transport; following that 48 organisms were tagged with a permanent marker and transferred to mesocosms.

2.2. Experimental set-up

The mussels were housed in eight mesocosms of 120 L capacity to allow double replication (rectangular glass tanks 100 cm long, 30 cm deep, 40 cm wide), each filled with 100 L of natural seawater (Cappello et al., 2011) collected directly from the station "Mare Sicilia" (38° 11′ 43.54″ N, 15° 34′ 24.729″ E; Messina, Italy) by a direct pipeline from the sea (mean seawater temperature 20 ± 1 °C). Six mesocosms (indicated as OIL, OIL + D and OIL + B) were supplemented with 70 ml of Arabian Light Crude Oil (ENI Technology S.p.A; 900 mg l^{-1}) prepared as previously indicated elsewhere (Cappello et al., 2006, 2007). A commercial dispersant (Bioversal 0.1% vol/vol_{OIL}, BIOECOTECH s.r.l.) was added to mesocosms OIL + D, while mesocosms OIL + B were equipped with a commercial system for continuous nano-bubble generation (OxyDoser™ PUREair, Oxydoser USA). Two mesocosms without any addition of crude oil, dispersant and/or nano-bubble generator were used as a pristine control (CTRL). All treatments lasted 48 h.

2.3. Respiration rate

Oxygen consumption rates were determined as a proxy for stress