ARTICLE IN PRESS

Environmental Pollution xxx (2016) 1–14

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Review

Oil spills and their impacts on sand beach invertebrate communities: A literature review☆

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ARTICLE INFO

Article history:
Received 6 June 2016
Received in revised form
28 July 2016
Accepted 28 July 2016
Available online xxx

Keywords:
Sand beach
Oil spill
Benthic invertebrates
Toxicity
Recovery

ABSTRACT

Sand beaches are highly dynamic habitats that can experience considerable impacts from oil spills. This review provides a synthesis of the scientific literature on major oil spills and their impacts on sand beaches, with emphasis on studies documenting effects and recoveries of intertidal invertebrate communities. One of the key observations arising from this review is that more attention has generally been given to studying the impacts of oil spills on invertebrates (mostly macrobenthos), and not to documenting their biological recovery. Biological recovery of sand beach invertebrates is highly dynamic, depending on several factors including site-specific physical properties and processes (e.g., sand grain size, beach exposure), the degree of oiling, depth of oil burial, and biological factors (e.g., species-specific life-history traits). Recovery of affected communities ranges from several weeks to several years, with longer recoveries generally associated with physical factors that facilitate oil persistence, or when cleanup activities are absent on heavily oiled beaches. There are considerable challenges in quantifying impacts from spills on sand beach invertebrates because of insufficient baseline information (e.g., distribution, abundance and composition), knowledge gaps in their natural variability (spatial and temporal), and inadequate sampling and replication during and after oil spills. Thus, environment assessments of impacts and recovery require a rigorous experimental design that controls for confounding sources of variability. General recommendations on sampling strategies and toxicity testing, and a preliminary framework for incorporating species-specific life history traits into future assessments are also provided.

1. Introduction

Sand beaches provide multiple ecosystem functions including the regulation of biogeochemical cycles (e.g., nutrients, water, organic carbon), shoreline buffering, maintenance of genetic and biological diversity through the provision of habitat to many species (including vertebrate populations, many of which are of conservation concern), support of natural processes that promote energy flow among biological systems, and provision of several human-related services including recreation (McLachlan and Brown, 2006; Schlacher et al., 2008). Because of their biological, physical, recreational, and cultural value, it is important to understand the impacts of oil spills on these habitats. Over the last decades there have been reviews of the impact of oil on shoreline habitats, including mangroves (Getter, 1982), marshes (Sell et al., 1995; Pezeshki et al., 2000; Michel and Rutherford, 2014), and rocky shores (Sell et al., 1995), as well as reviews on general oil spill impacts (Gundlach and Hayes, 1978; Vandermeulen et al., 1982; Teal and Howarth, 1984; Kingston et al., 2003; NRC, 2003). However, similar efforts have not been undertaken for sand beaches, despite the fact that these habitats are commonly oiled following an oil spill. The goal of this review is to synthesize the literature on the impacts of oil spills on sand beaches (0.0625–1 mm grain size) with emphasis on impacts to intertidal invertebrate communities and their recovery. This synthesis required an extensive evaluation of published literature resulting in the inclusion of peer-reviewed papers and reports on field or laboratory research undertaken following oil spills or field experimental studies. Because of the relatively small number of identified publications, most research was included in this review noting any potential shortcomings or limitations with specific studies.

☆ This paper has been recommended for acceptance by Maria Cristina Fossi.

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http://dx.doi.org/10.1016/j.envpol.2016.07.065
0269-7491/

Please cite this article in press as: Bejarano, A.C., Michel, J., Oil spills and their impacts on sand beach invertebrate communities: A literature review, Environmental Pollution (2016), http://dx.doi.org/10.1016/j.envpol.2016.07.065

1.1. An overview of sand beach invertebrate communities

Sand beaches are inhabited by complex and specialized biotic assemblages encompassing interstitial primary producers and decomposers, and secondary producers (meiofauna and macrofauna) including predators and scavengers (e.g., ghost crabs, terrestrial mammals, shorebirds). Invertebrate communities on sand beaches are often dominated by a handful of species, which combined contribute significantly to the overall energy budget of these habitats. As noted decades ago by Warwick and Clarke (1984), functional traits of the marine benthos follow a bimodal size distribution corresponding to two key invertebrate groups of interest in this review: meiofauna and macrofauna. As a result, these two components of the benthic fauna occupy different niches in sand beach habitats.

A large number of meiofauna species (organisms that pass through a 1 mm sieve and are retained by a 45 µm sieve) share adaptations associated with small size including: 1) direct benthic development; 2) dispersal as adults; 3) short generation times; 4) generally semelparous reproduction, 5) growth that reaches an asymptotic body size; 6) discriminate feeding of particles selected by size and shape; and 7) high motility (Warwick and Clarke, 1984). This assemblage is typically found in interstitial sands above the water table, where they feed on dissolved and particulate organic matter. While the meiobenthos are numerically dominated by nematodes and harpacticoid copepods, other members of this assemblage include gastrotrichs, oligochaetes, ostracods and turbellarians, and non-permanent members (larvae and juveniles) of macrofauna species (McIntyre, 1969; McLachlan, 1983; Kennedy and Jacoby, 1999). Their spatial distribution is largely controlled by grain size, temperature, salinity, moisture content, redox potential, and organic input (McIntyre, 1969; McLachlan, 1983; McLachlan and Brown, 2006), and their cyclic migrations are associated with tidal and diurnal cycles and seasons (McLachlan, 1983; McLachlan and Brown, 2006). These members of the benthic community are generally short lived (egg to egg production of weeks to a few months), have high reproductive rates (2–4 generations per year), and play an important role in nutrient cycling within the interstitial environment (McIntyre, 1969; McLachlan, 1983). Beach meiofauna also comprise an important food source to higher trophic predators (e.g., shorebirds, crabs) (McLachlan and Brown, 2006). On most sand beaches, meiofauna are richer and more diverse than macrofauna (McLachlan and Brown, 2006), and although their numerical abundance exceeds that of macrofauna (average ratio: 10^5 to 1), their biomass is substantially lower (average ratio: 1:5) (McLachlan, 1985). Despite their abundance and diversity, this sand beach community has not been extensively studied, and relatively little is known about their spatio-temporal patterns across various beach types (McLachlan and Brown, 2006). Although meiofauna play important nutrient mineralizing and cycling roles in sand beaches, there are disadvantages to their use in environmental monitoring, including their diminutive size, high microscale spatial variability, and high diversity with limited taxonomic literature (Kennedy and Jacoby, 1999).

In contrast, beach macrofauna (organisms retained by 500 µm mesh sieve) have generally been well studied, and they are more often used in monitoring because of their size and ecological role as an important prey to higher trophic levels (e.g., Schlacher et al., 2016). Macrofauna have adaptations that are remarkably different from those of meiofauna: 1) planktonic larval development and dispersal; 2) greater than 1 year generation times; 3) generally iteroparous reproduction and continuous growth; 4) indiscriminate feeding on particles; and 5) mobility that ranges from sedentary to motile (Warwick and Clarke, 1984). This assemblage is comprised of bivalve mollusks, decapod crustaceans, polychaetes, amphipods, and isopods. Macrofauna, with some exceptions, are most common at the sand surface and in relatively shallow burrows, where they feed on particulate organic matter (allochthonous and autochthonous) (McLachlan and Brown, 2006) and planktonic food sources in the swash zone which is constantly replenished by wave action. The spatial distribution of macrobenthos is influenced by several factors, including sand grain size, moisture and organic content, beach slope, wave action, season, and large disturbance events (e.g., storms) (see McLachlan, 1983). Although their dry biomass varies widely across beach types, it tends to increase with wave exposure (McLachlan, 1983, 1996). Despite their relatively high biomass, only a relatively small number of macrofauna species are adapted to this harsh environment, where at any single beach the number rarely exceeds 20 species (McLachlan and Brown, 2006).

The distribution of macrobenthos on sand beaches has been extensively documented. The intertidal zone of sand beaches, the area between the low and high water tide, is divided into three boundary not necessarily rigid in their extent: the upper, middle and lower intertidal zones (Dahl, 1952). These zones grade into each other, and therefore, there is substantial overlap in species composition across zones. The uppermost part of the beach beyond the upper intertidal zone is the supratidal zone, an area above the high tide occasionally flooded during high spring tides and storms. Typical fauna of the upper and supratidal zones include air breathing invertebrates (ghost crabs *Ocypode quadrata*, and talitrid amphipods [e.g., *Orchestia, Allorchestes, Talitrus*]). The boundary between these two zones is ecologically important because it is where the drift line of macrophyte wrack accumulates. This wrack zone provides important habitat for up to 40% of the intertidal species on sand beaches, harboring crustaceans (talitrid and haustoriid amphipods [e.g., *Haustorius*], crabs, isopods [e.g., *Tylos*]) and non-aquatic invertebrates (insects) (Dugan et al., 2003; Defeo et al., 2009). Furthermore, macrophyte wrack provides an important allochthonous source of carbon and organic material influencing the trophic structure of macrobenthos on sand beaches (McLachlan, 1985; Dugan et al., 2003; McLachlan and Brown, 2006; Dugan et al., 2011). Fauna typical of the middle intertidal include isopods (e.g., *Eurydice*), while those of the lower intertidal zone include haustoriid and gamarid (e.g., *Ampelisca*, *Gammarus*, *Pontocrates*) amphipods, polychaetes (e.g., *Dispio*, *Nephtys*, *Scolelepis squamata*), coquinas (*Donax*), and crabs (*Emerita*). Although the shallow subtidal zone, commonly inhabited by bivalves and crabs, is functionally part of the sand beach system, for the purpose of this review, emphasis is placed on intertidal species.

Because of the biochemical and ecological importance of benthic invertebrates on sand beaches, understanding their response to and recovery from oil spills is important to adequately assess impacts on these habitats and their ecological services.

1.2. Oil behavior and persistence in sand beaches

Although the focus of this review is not on physical factors that influence oil persistence, a brief discussion is included on drivers that limit oil degradation and weathering while facilitating exposure of beach invertebrates. The greatest amount of oil strands on sand beaches during an onshore wind and a falling tide, where oil is deposited on the entire intertidal zone. However, oil does not readily penetrate into wet, water-saturated sand in the lower intertidal zone. As the tide rises and waves break on the beach, oil is lifted off the sand and concentrated at and above the high-tide line, an area of ecological importance because of the accumulation of wrack.

Oil penetration into fine-grained sand (0.0625–0.25 mm size) is

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