Research papers

Assessment of benthic disturbance associated with stingray foraging for ghost shrimp by aerial survey over an intertidal sandflat

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ARTICLE INFO

ABSTRACT

One notable type of bioturbation in marine soft sediments involves the excavation of large pits and displacement of sediment associated with predator foraging for infaunal benthos. Batoids are among the most powerful excavators, yet their impact on sediment has been poorly studied. For expansive tidal flats, only relatively small proportions of the habitat can be sampled due to physical and logistical constraints. The knowledge of the dynamics of these habitats, including the spatial and temporal distribution of ray bioturbation, thus remains limited. We combined the use of aerial photogrammetry and *in situ* benthic sampling to quantify stingray feeding pits in Tomioka Bay, Amakusa, Japan. Specifically, we mapped newly-formed pits over an 11-ha section of an intertidal sandflat over two consecutive daytime low tides. Pit size and distribution patterns were assumed to scale with fish size and reflect size-specific feeding behaviors, respectively. *In situ* benthic surveys were conducted for sandflat-surface elevation and prey density (callianassid shrimp). The volume versus area relationship was established as a logistic function for pits of varying sizes by photographing and refilling them with sediment. This relationship was applied to the area of every pit detected by air to estimate volume, in which special attention was paid to ray ontogenetic change in space utilization patterns. In total, 18,103 new pits were formed per day, with a mean individual area of 1060 cm^2. The pits were divided into six groups (G1 to G6 in increasing areas), with abundances of G1, G2+G3, and G4−G6 being medium, high, and low, respectively. Statistical analyses using generalized linear models revealed a marked preference for the higher prey-density areas in G1 and the restriction of feeding grounds of G4−G6 to the lower shore, with G2+G3 being generalists for prey density and sandflat elevation. The lower degrees of overall bioturbation by G1 and G4−G6 were spatially structured for the eight sub-areas demarcated by prey density and sandflat elevation, while G2+G3 homogenized the state over the sandflat. The newly-formed pits' sub-areal mean numerical, excavated-areal, and displaced-sediment-volume densities per day were confined to small ranges: 0.14–0.17 m^{-2}, 132–223 cm^2 m^{-2}, and 551–879 cm^3 m^{-2} (latter two including 119 shallow non-pit excavations). These bioturbation rates are positioned at relatively high levels compared with those by rays from other geographic regions. The present procedure is applicable to the assessment of disturbance by any surface-sediment excavators on tidal flats if their pit dimensions are discernible from the air.

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1. Introduction

The excavation of large pits and displacement of corresponding amounts of sediment associated with predator foraging for infaunal macrobenthos or megaherbivore grazing on epibenthic vegetation are classic examples of bioturbation in marine and estuarine soft-sediment habitats (Bromley, 1996; Cadée, 2001; Hall et al., 1994; Meysman et al., 2006). In the marine bioturbator classification, these consumers are regarded as large epifaunal biodiffusors (Kristensen et al., 2012). This group includes vertebrates such as

gray whale (Johnson and Nelson, 1984; Weitkamp et al., 1992), walrus (Oliver et al., 1985), sea otter (Hines and Loughlin, 1980), dugong (Preen, 1995; Skilleter et al., 2007), birds (Cadée, 1990; Nacken and Reise, 2000), sea turtle (Lazar et al., 2011) and demersal fish (Howard et al., 1977; Orth, 1975; Yahel et al., 2002), and invertebrates such as horseshoe crab (Botton, 1984; Woodin, 1978) and decapod crabs (Thrush, 1986; Woodin, 1978). The considerable modification of seabed topographies by these organisms is accompanied by sedimentological and biogeochemical consequences for the ambient environment originally set by current and wave actions, such as sediment and nutrient resuspension into the water column (Johnson and Nelson, 1984; Ray et al., 2006; Yahel et al., 2008; Yahel et al., 2002), detritus accumulation in pits (Hall et al., 1991; VanBlaricom, 1982), lateral transport

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of displaced sediment (Grant, 1983; Johnson and Nelson, 1984), and vertical mixing of this sediment in the substratum column (D'Andrea et al., 2004).

One major limitation to the assessment of high-magnitude epifaunal biodiffusors' pit formation and concurrent sediment displacement lies in the difficulty to cover a sufficiently large area of the seabed with inherent spatial heterogeneity. Small-scale observations would not necessarily be extrapolated to an unexplored larger area. For predators excavating feeding pits, the "total area" needed for full assessment depends on the availability of information on pit size-frequency distribution, density, local dispersion pattern, and landscape-scale distribution (Hall et al., 1994). Sampling these areas in the field is constrained by low-tide times for intertidal assessments and to scuba limitations for subtidal beds. Thus, these techniques generally cover relatively small proportions of the seabed, between 50 and 26,900 m^2 (Cadée, 1990; D'Andrea et al., 2004; Grant, 1983; Hall et al., 1991; Hines et al., 1997; Myrick and Flessa, 1996; Nacken and Reise, 2000; O'Shea et al., 2012; Thrush, 1986; Thrush et al., 1991; VanBlaricom, 1982; Woodin, 1978). Several attempts have been undertaken to cover larger areas. For a 20–40-m deep, 22,000-km^2 bed of the northeastern Bering Shelf, side-scan sonar was used to detect feeding excavations by gray whales and walruses (Johnson and Nelson, 1984; Nelson et al., 1987; Ray et al., 2006). Aerial and/or boat-based censuses have also been previously used to map epifaunal bioturbator impacts in shallow subtidal beds with high water clarity. These methods have been applied to vegetation patches resulting from grazing by dugongs in seagrass beds with up to a 110-km^2 area (Preen, 1995) and from cownose ray digging in eelgrass beds up to a 24-ha area (Hovel and Lipcius, 2001; Orth, 1975) and pits formed by stingrays in a 1-km^2 lagoon (O'Shea et al., 2012). Aerial surveys have been least used for intertidal zones, with only one study of gray whale pits along a 90–180-km stretch of Puget Sound shoreline in Washington, U.S.A. (Weitkamp et al., 1992) and another on horseshoe crab pits by digital camera moving along a 50-m long cable (Lee, 2010).

Of the demersal fish epifaunal biodiffusors in soft-sediment habitats, rays (Chondrichthyes: Batoidea) are among the most powerful excavators that can make large pits (e.g. 1-m wide and 10s-cm deep) as they prey on deep-dwelling infauna from sandy substrate (Cadée, 2001; Kristensen et al., 2012). Preys are mined hydraulically by jetting water from the mouth or gills (Gregory et al., 1979; Sasko et al., 2006). Prey targeted in these habitats vary among ray taxa; cownose rays and eagle rays generally select bivalve mollusks (Ajemian et al., 2012; Hines et al., 1997; Peterson et al., 2001), while stingrays favor decapod crustaceans and fish (Ebert and Cowley, 2003; Howard et al., 1977; Taniuchi and Shimizu, 1993; Tillett et al., 2008). Some studies suggest that density-dependent foraging behaviors of rays could stabilize local prey populations (Ajemian et al., 2012; Hines et al., 1997) and bring about prey metapopulation source–sink dynamics (Peterson et al., 2001).

Two measures associated with ray pit excavations have been considered as their basic bioturbation rates: (1) numerical density and distribution of newly-formed pits with various horizontal and vertical dimensions and (2) volumetric density and distribution of sediment displaced aside newly-formed pits. To date, only a handful of estimates have been presented for these measures, which were generally extracted from a small portion of each study site (Cross and Curran, 2004; D'Andrea et al., 2004; Grant, 1983; Hines et al., 1997; Myrick and Flessa, 1996; O'Shea et al., 2012; Reidenauer and Thistle, 1981; Sherman et al., 1983; Thrush et al., 1991; Valentine et al., 1994; VanBlaricom, 1982). It is only after the proper assessment of these bioturbation rates that the subsequent processes of lateral transport of discarded sediment and vertical mixing in the substratum column can be evaluated (D'Andrea et

al., 2004; Myrick and Flessa, 1996). Aerial methods can be a strategic tool to help enlarge the survey areas that likely contain high spatial heterogeneity in each habitat type, especially within intertidal zones that have limited access due to tidal activity. The ray bioturbation rates can vary spatially, depending on the physical setting of feeding grounds and the prey-density distribution. Physical components of heterogenetiy in intertidal zones include: thickness of sediment column in which deep-dwelling benthic prey can escape from surface disturbance, and surface topographic elevation. The latter component is particularly relevant to high-tide predators like stingrays, which access this zone from the subtidal region and are thus at risk of being stranded with receding tides. Regarding the influence of prey abundance, only Hines et al. (1997) described a spatially varying prey-density-dependent pit-excavation rates for eagle rays. Finally, for estimating the volume of displaced sediment from pits, semi-ellipsoid or inverted-cone approximation to pit shape has sometimes been made, with circular or elliptical area and maximum depth given (Cross and Curran, 2004; D'Andrea et al., 2004; O'Shea et al., 2012), but more reliable estimates can be obtained by direct refilling of pits (Myrick and Flessa, 1996).

Long-term observations (1979–2001) of the benthic community on an intertidal sandflat in Amakusa-Shimoshima Island, western Kyushu, southern Japan (Fig. 1) indicated an abrupt increase in pits formed by the stingray, *Dasyatis akajei* (Müller & Henle) from 1995 (Flach and Tamaki, 2001; Harada and Tamaki, 2004). Based on a long-term (1972–2001) annual fishery landing record from the four prefectural governments surrounding Ariake Sound adjacent to the present study area, Yamaguchi (2005) summarized trends in the abundance of rays and sharks in the sound: (1) rays increased steadily to reach a maximum during 1988 to 1995 and thereafter decreased to a level which was still higher than those before 1985, (2) *D. akajei* accounted for most of these rays, and (3) sharks decreased largely continuously to 1997, with a subsequent slight increase. In Amakusa, the stingray almost exclusively forages on ghost shrimp (Decapoda: Axiidea: Callianassidae), *Nihonotrypaea harmandi* (Bouvier), the most dominant species in biomass in the benthic community (Flach and Tamaki, 2001; Harada and Tamaki, 2004). In other parts of the world, ghost shrimps co-occur with ray pits in intertidal-flat habitats (D'Andrea et al., 2004; Martinell et al., 2001; Myrick and Flessa, 1996) and are reported to be a major prey item for dasyatid stingrays (Ebert and Cowley, 2003; Howard et al., 1977; Tillett et al., 2008). In Amakusa, the decline of the ghost shrimp population occurring since 1995 has been attributed to increased predation pressure by *D. akajei*, which has induced cascading effects on other members of the benthic community (Flach and Tamaki, 2001; Harada and Tamaki, 2004; Mandal et al., 2010). A similar chain of events originally caused by *D. akajei* population increase was recently documented for an intertidal sandflat community in Ariake Sound (Takeuchi et al., 2013). However, pit-related bioturbation rates on the sandflat in Amakusa remain to be quantified except for some preliminary data (Harada and Tamaki, 2004); until around 2000, the manual census of stingray feeding pits during low-tide hours was not entirely impossible at least for a narrow strip along tidal gradient. Most recently, this is no longer feasible due to the overwhelming pit density.

The first objective of the present study was to construct digitized maps of newly-formed stingray pits over an 11-ha section of the above intertidal sandflat in Amakusa. As the most basic premise of the study, pit size and distribution patterns were assumed to scale with fish size and reflect size-specific feeding behaviors, respectively (Hall et al., 1994; Hines et al., 1997). Following the result of a pilot aerial survey, a main aerial survey over two consecutive daytime low tides was performed to detect pits formed in one day. At the same time, benthic surveys were