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Author(s): Marjorie J. Wonham and Michael W. Hart
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Marjorie J. Wonham[1], Quest University Canada, 3200 University Blvd., Squamish, British Columbia, Canada V8B 0N8 *and* Bamfield Marine Sciences Centre, 120 Pachena Rd., Bamfield, BC, Canada, V0R 1B0

and

Michael W. Hart, Department of Biological Sciences, Simon Fraser University, 8888 University Drive, Burnaby, BC, Canada, V5A 1S6

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Abstract

Many marine species are shifting poleward with global climate change, and many move on a shorter-term basis with periodic climate variations such as the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). The Pacific sand crab *Emerita analoga* (Crustacea: Decapoda: Anomura: Hippidae) is a dominant member of the wave-exposed sandy beach macrofauna of California and Oregon. Its occasional records from Washington to Alaska have been taken to correspond to ENSO events. However, there are surprisingly few scientific or citizen-science records of its presence in this region. We report the first published record in over 30 years of *E. analoga* in British Columbia, and summarize historical published and unpublished records. Because this species is conspicuous and readily identifiable, we suggest the general absence of its published, institutional, and citizen-science records coincident with most historical ENSO events may be due to a lack of reporting. In California, *E. analoga* accumulates harmful algal bloom toxins, is consumed by crabs, fish, birds, and marine and terrestrial mammals, and serves as the intermediate host for a variety of parasites, including the peritonitis-inducing acanthocephalan implicated in sea otter mortalities. As coastal waters warm, we predict that *E. analoga* will colonize sandy beaches north of its current range, where it may serve as an abundant prey item and as a vector for the trophic transfer of toxins and parasites. Detecting changes in its abundance will require the continued observation and reporting of its records, which we encourage in academic, government, and citizen-science venues.

Keywords: decapoda, parasites, Pacific Decadal Oscillation, climate change, citizen science

Introduction

Documenting Range Extensions

The distributional ranges of many marine species are shifting poleward with global climate change (Johnson et al. 2011, Sorte et al. 2010). Shorter-term climate oscillations, such as the warm phases of the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), also cause periodic poleward range shifts by accelerating ocean currents and planktonic larval dispersal (e.g., Yamada et al. 2015) or extending the latitudinal range of physiological limits such as water temperature (e.g., Hilbish et al. 2010). Such range shifts may have important ecological effects on species composition and trophic

[1]Author to whom correspondence should be addressed. Email: marjorie.wonham@questu.ca

dynamics (Pearcy and Schoener 1987; Keister et al. 2005, 2011). Records of species distributions and extensions can serve as biological indicators of ocean-current and climatic phenomena (e.g. Johnson 1939, Sorte et al. 2001, Diehl et al. 2007, Behrens Yamada and Kosro 2010, Kuo and Sanford 2013), but do so only if they are reported. However, new populations—particularly low density, localized, or ephemeral ones—may remain unobserved; if observed, their observations may remain unrecorded; if recorded, their records may remain unpublished.

Unpublished species records may be found in museum, university, and government-agency databases, and more recently in citizen-science databases. Citizen-science initiatives, ranging from active data-collection programs to passive contributory databases, can draw on large numbers of observers to increase the opportunity for species to be noticed, recorded, and reported, and have contributed to the documentation of climate-induced range shifts (Dickinson et al. 2012, Thiel et al. 2014). As with all collections and databases, the value of citizen-science data depends on the motivation of contributors to submit information, and on the quality control exerted over the identifications (Dickinson et al. 2012).

Northern Records of a Southern Crab

The Pacific sand crab (*Emerita analoga*) (Stimpson 1857) is a conspicuous and patchily abundant intertidal filter feeder on wave exposed sandy beaches of the northern and southern temperate eastern Pacific (Dugan et al. 2003, Dawson et al. 2011). Females reach approximately 3 cm in length (males are approximately half the size): it is thus a relatively large organism in a habitat occupied by relatively few conspicuous macroinvertebrates. In California and Oregon it is abundant and persistent, although its Oregon population appears to be largely supplied by recruitment from California (Sorte et al. 2001). In Washington, British Columbia, and Alaska, its occasional appearance has been interpreted to correspond with the northward extension of warm-water currents during ENSO events (Pearcy and Schoener 1987, Austin 2000). Given its densities and size, *E. analoga* is a likely candidate for both published and citizen-science database records of its northern range extensions. However, there are surprisingly few records of this species north of its primary range (Table 1).

Methods

We first noticed *E. analoga* on Keeha Beach, a wave-exposed sandy beach on Vancouver Island, British Columbia (48°47’05”, 125°11’09”). The animals were observed serendipitously during haphazard exploration by the Bamfield Marine Sciences Centre (BMSC) Marine Invertebrate Zoology class on 26 May 2016. Although we had explored this same section of beach at the same time of year in annual field trips (2006 and 2008–2015), with similarly unstructured but wide-ranging intertidal meanderings by a group of 15–22 students, we had not previously seen this species here. One of us (MW) subsequently searched at low tide along two similar beaches on the outer coast of Vancouver Island: several kilometers along Wickanninish Beach (49°02’00”, 125°41’33”) on 28 May 2016, and 1 km along Pachena Beach (48°47’39”, 125°07’18”) on 14 July 2016. The animals we observed were photographed, and identified using a regional key (Carlton 2007) with confirmation by G. Jensen (University of Washington).

To compile additional records of *E. analoga* north of Oregon, we reviewed the literature and queried institutional and citizen-science collections and databases. For institutions, we queried those listed in the scientific literature as repositories of the northern *E. analoga* collections: California Academy of Sciences; Canadian Museum of Nature, Ottawa; Royal British Columbia Museum, British Columbia (RBCM); Naturalis Biodiversity Center (NBC; formerly the Rijksmuseum van Natuurlijke Historie, Netherlands); Scripps Institute of Oceanography (SOI), California; National Museum of Natural History; Smithsonian Institution, Washington, DC (formerly the United States National Museum). We also queried additional institutions in Canada and the United States with collections or databases for our region: American Museum of Natural History (AMNH), New York; Burke Museum of Natural History and Culture at the University of Washington (BMUW); Beaty

TABLE 1. Pacific sand crab *Emerita analoga* records from Alaska (AK), Washington (WA), and British Columbia (BC), including Vancouver Island (VI). Gravid indicates whether ≥ 1 gravid females were reported in ≥ 1 of the records (Yes or No). Source is citation (with repository in parentheses) or accession number, as applicable: CAS, California Academy of Sciences; CMNC, Canadian Museum of Nature; EFBC, E-Fauna BC; ONP, Olympic National Park; PRNPR, Pacific Rim National Park Reserve; RBCM, Royal British Columbia Museum; RMNH, Naturalis Biodiversity Center (formerly Rijksmuseum Natuurlijke Historie); SOI, Scripps Institute of Oceanography; USNM, Smithsonian Natural History Museum (formerly United States National Museum).

Year	Locations	Province /State	Gravid	Source
1903	Karluk, Kodiak Island	AK	Y	Efford 1969 (CAS)
1941, 1942	Columbia River to Kalaloch Beach	WA	Y	Banner and McKernan 1943 (USNM)
1957	Fraser River	BC	N	RBCM 957-00840-002 (coll. not recorded)
1958, 1959, 1960, 1961	Wickanninish Beach	BC (VI)	Y	Butler 1959, Hart 1984 (the sole 1961 record is of a carapace)
1959, 1960	Long Beach	BC (VI)	Y	Efford 1969, 1976 (RBCM, RMNH, CMNC, SIO)
1983	nd	WA	nd	Schoener and Fluharty 1985
1983	Wickanninish Beach	BC (VI)	nd	RBCM 984-00116-001 (carapace only; coll. H. Plewes)
1983	Kyuquot Sound	BC (VI)	N	Fulton and LeBrasseur 1985
2006, 2007, 2008	ONP beaches	WA	nd	Steven Fradkin, Marine Ecologist, ONP, pers. comm. to MW
2015, 2016	ONP beaches; Shi Shi Beach	WA	Y	Steven Fradkin, Marine Ecologist, ONP, pers. comm. to MW; ONP Bioblitz (iNaturalist)
2016	Keeha Beach; Wickanninish Beach	BC (VI)	Y	present study (EFBC)
2016	Wickanninish Beach; Long Beach; Florencia Beach	BC (VI)	Y	Sarah Tyne, Resource Management Officer, RPNPR (PacRim_SAR_Kestrel database), pers. comm. to MW

Biodiversity Museum (BBM) at the University of British Columbia, Bamfield Marine Sciences Centre (BMSC), British Columbia; the Center for Alaskan Coastal Studies (CACS); the University of Alaska Museum f the North (UAMN); and two national parks (Pacific Rim National Park Reserve, British Columbia, and Olympic National Park, Washington).

For citizen science we queried two online searchable databases. The University of British Columbia's E-fauna allows registered users to contribute georeferenced photos of organisms, whose identifications are vetted by experts (E-Fauna BC 2015). The California Academy of Science's iNaturalist is a global social-media platform for sharing organism photos; its category of "research grade" observations consists of geo-referenced images with > 2/3 user agreement on the identification, and includes records from many Bioblitz surveys (iNaturalist 2016).

Results

New Records

We report new records and summarize additional published and unpublished records of *E. analoga* north of Oregon (Table 1). On Keeha Beach, live *E. analoga* were found by the handful along the swash zone of a short (~ 100m) stretch of beach (Figure 1). On Wickanninish Beach, adult and juvenile molts were abundant along approximately 5 km of the strand line and one live gravid female was found (Figure 1). On Pachena Beach, neither molts nor live individuals were found.

Figure 1. Pacific sand crab (*Emerita analoga*) on Long Beach, British Columbia, 2016, showing a) adult and juvenile molts along the strand line, b) live gravid female dorsal view, c) ventral view.

Institutional and Citizen-Science Records

Queries of institutional databases added previously unpublished records from the RBCM and from two national parks (Table 1). Within the citizen-science databases, the University of British Columbia's E-fauna contained no *E. analoga* observations. In the California Academy of Science's iNaturalist we found 192 observations, of which only one, from ONP, was in our region of interest (Table 1).

Discussion

Coincidence with ENSO Events

Although *E. analoga* records north of its typical range have been attributed to ENSO events, its known records correspond to only a few of these events over the last century (Figure 2). The conspicuous absence of records coinciding with most ENSO events could indicate that during those events *E. analoga* did not recruit here, or was not observed, or was not identified, or was not documented in published or citizen-science venues. Because the dispersal of its larvae is at the mercy of coastal currents, we have no reason to believe they would not have arrived during other ENSO events, particularly those enhanced by the warm phase of the PDO (most recently 1977–1999; NASA 2016). Because there are few other conspicuous species of the same size range in this habitat, it would likely have attracted the notice of beachgoers or biologists familiar with the regional biota, if it had been seen. And because there are no other species morphologically or phylogenetically close to *E. analoga* on exposed sandy beaches from Washington to Alaska, it would be unlikely to be confused with anything else. Three other somewhat similar species do overlap with *E. analoga* in other parts of its range. The tropical eastern Pacific congener *E. rathbunae* is distributed from Mexico to Chile, but unlike *E. analoga* has transverse ridges cov-

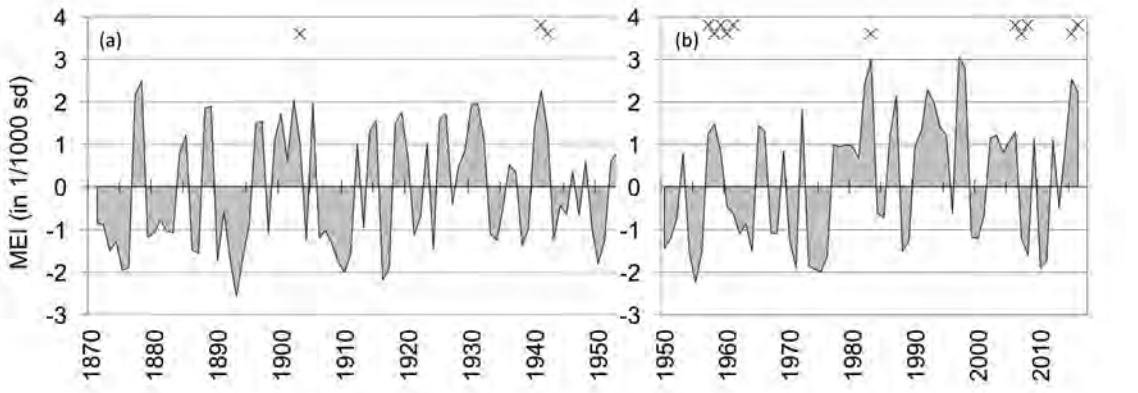

Figure 2. Annual maximum value (negative or positive) of the bimonthly Multivariate ENSO Index (MEI), expressed in 1/1000 standard deviations: a) From 1871–1955 (standardized to years 1871–2005), and b) From 1950–2016 (standardized to monthly-updated values 1950–1/2017). Data plotted from the NOAA MEI and MEI.ext computations at https://www.esrl.noaa.gov/psd/enso/mei.ext/ (last accessed 18 February 2017) (Wolter and Timlin 2011). Note overlap between panels from 1950–1955. Years of known *Emerita analoga* records from WA, BC, or AK indicated with ×; vertical jittering is for clarity only.

ering the carapace (Hsueh 2015). The California mole crab (*Lepidopa californica*) and the Southern California spiny mole crab (*Blepharipoda occidentalis*) overlap with *E. analoga* in southern California: both are white, chelate or subchelate, with one or more anterolateral spines on the carapace, whereas *E. analoga* is grey and lacks both claws and anterolateral carapace spines (Carlton 2007). None of these three congeners are known from northern beaches of Washington to Alaska. With respect to Wickanninish Beach, BC, Hart (1984) reported that "[o]ld-time residents in the area tell of earlier invasions," and two local residents commented in 2016 (to MW) that they had in the past periodically observed *E. analoga* on the beach. We therefore suggest that *E. analoga* has recruited here during past ENSO events, has likely been observed and even identified, but on most occasions simply has not been documented.

Ecological Implications of Range Extension

Like other sand crabs, *E. analoga* migrates up and down the beach with the tide while burrowing into the sand and filter feeding in the swash using its antennae. Its lifespan of 2–3 years includes an estimated planktonic larval duration of several months; adults reach approximately 1–3 cm in carapace length (Efford 1969, Sorte et al. 2001, Kolloru et al. 2011). On sandy beaches in California, *E. analoga* can be abundant and dominant, reaching thousands to tens of thousands per meter of beach, and constituting over 80–90% of intertidal invertebrate abundance and biomass (Dugan et al. 2003, Wooldridge et al. 2016). In Peru, it serves as a host for epizoic macroalgae and mussels (Villegas et al. 2006, Hidalgo et al. 2010).

As a filter feeder, *E. analoga* accumulates both domoic acid (DA), the cause of amnesic shellfish poisoning and paralytic shellfish poisoning toxins (PSPT), which can alter the foraging behavior of predatory birds and sea otters (Kvitek and Bretz 2005, Kvitek et al. 2008). Known predators of *E. analoga* include brachyuran crabs, fishes, birds, and marine and terrestrial mammals (MacGinitie 1938, Lafferty and Gerber 2002, Elgueta et al. 2007, Iannacone et al. 2007, Kolloru et al. 2011). We predict that local species in those taxa, including the maritime mammals that consume intertidal organisms in our region (rodents, mustelids, raccoons, foxes, wolves, and bears; Carlton and Hodder 2003, Darimont et al. 2004), may increasingly consume *E. analoga*.

Emerita analoga is also an intermediate host for acanthocephalan, nematode, trematode, and

cestode parasites of fishes, birds, and mammals (Smith 2007, Iannacone et al. 2007, Kolloru et al. 2011). Acanthocephalan infection prevalence in California can be up to 60–69%, with a maximum abundance of 2–20 crab^{-1} (Smith 2007, Kolloru et al. 2011). In the endangered Southern sea otter (*Enhydra lutris nereis*), acanthocephalan peritonitis contracted from consuming sand crabs including *E. analoga* caused an estimated 14% of mortalities in the 1990s (Lafferty and Gerber 2002). As Northern sea otters (*E. lutris kenyoni*) recolonize southwards (Fisher et al. 2014), they may encounter this additional parasite burden, particularly during ENSO events.

We predict that with generally warming waters and the predicted increasing frequency of ENSO events (Cai et al. 2014), combined with the absence of related or functionally similar species on exposed sandy beaches of the northeastern Pacific, *E. analoga* will come to colonize this region. The presence of gravid females suggests not only that their larvae can arrive from points south, but also that the conditions permit growth and reproduction. Warm-water phases of the ENSO and PDO are thus likely to facilitate the establishment of beachhead populations. As a species that reaches high densities, is consumed by a range of predators, accumulates DA and PSPT, and is the intermediate host to a variety of parasites affecting vertebrate hosts, it has the potential to play an important role in the regional ecology. To help document recruitment pulses and range shifts in *E. analoga*, and other species, we encourage improved reporting and compilation of published, government, and citizen-science records.

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