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Will the European green crab (*Carcinus maenas*) persist in the Pacific Northwest?

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A strong cohort of young European green crabs (*Carcinus maenas*) appeared in North American embayments from Oregon to the west coast of Vancouver Island following the strong *El Niño* of 1997/1998. Unusually, strong north-moving coastal currents transported crab larvae from established source populations in California to the Pacific Northwest. Since then, both coastal transport and recruitment of young green crabs have been weaker. Although it was predicted that green crabs would become extinct in the Pacific Northwest once the original colonists died of senescence at about age 6, this has not happened. Age-class analysis and the appearance of young crabs evidence the existence of local recruitment in the Pacific Northwest, especially after warm winters. An extensive survey by Fisheries and Oceans Canada found populations of green crabs on the west coast of Vancouver Island, with densities of >2 per trap in some inlets. However, no green crabs were found in the inland sea between Vancouver Island and the mainland. Therefore, outreach efforts should continue to prevent the establishment of this invader in those waters via ballast water or shellfish transport.

Keywords: *Carcinus maenas*, European green crab, introduced species, Pacific Northwest.

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Introduction

The European green crab (*Carcinus maenas*), a well-documented invasive species, competes with native crab species and preys on clams, mussels, and other species in natural settings and in aquaculture (Cohen *et al*., 1995; Grosholz and Ruiz, 1995; Grosholz *et al*., 2000; Behrens Yamada, 2001; McDonald *et al*., 2001; Jensen *et al*., 2002). Its native range is from Mauritania in northwestern Africa through Atlantic Europe to northern Norway and Iceland. However, it has become established in South Africa, eastern Australia, Tasmania, the Patagonian coast of South America, the Atlantic coast of North America (from Virginia to Prince Edward Island), and the Pacific coast of North America (Le Roux *et al*., 1990; Grosholz and Ruiz, 1995; Jamieson, 2002; Carlton and Cohen, 2003; Ahyong, 2005; Behrens Yamada *et al*., 2005; Cameron and Metaxas, 2005; Hidalgo *et al*., 2005).

European green crabs were first detected on the Pacific coast in San Francisco Bay in 1989, but likely arrived before that, populations taking time to become established and liable to detection (Cohen *et al*., 1995; Grosholz and Ruiz, 1995). Likely vectors are thought to be discarded packing materials (seaweed) for Atlantic seafood products or bait worms (Behrens Yamada, 2001), or the ballast water transport of larvae. Bagley and Geller (2000) used molecular genetics to determine that the founding population was from the Atlantic coast of North America.

Dispersal from San Francisco Bay was through the spread and settlement of pelagic larvae (Grosholz and Ruiz, 1995; Behrens Yamada and Hunt, 2000; Behrens Yamada, 2001). Increases in distributional limits were episodic, green crabs spreading to Bolinas Lagoon, Drakes Estero, Tamales Bay, Bodega Harbour, and Humboldt Bay in 1993, to Oregon in 1995 or 1996, and to Washington and British Columbia during the 1997/1998 *El Niño* episode (Grosholz and Ruiz, 1995; Miller, 1996; Behrens Yamada and Hunt, 2000). The known range in 2000 was from Morro Bay, California, to British Columbia. Here, we report the status of green crabs in the Pacific Northwest, 10 years after they were first discovered by an oyster grower in Coos Bay, Oregon.

Methods

Trapping

Sampling methods and trap types were standardized through time and space. We used Folding Fukui fish traps (63 × 46 × 23 cm; 1.6 cm mesh), with wide, slit-like openings to target adult crabs >40 mm carapace width (CW). Minnow or crayfish traps (21 × 37 cm), with 6 cm openings and 0.5 cm mesh, were used to target late-stage "young-of-the-year" crabs. These crabs start entering traps when they reach ~25 mm CW. Pitfall traps, five-gallon buckets buried so that their lips are flush with the sediment, were only used at a high marsh site in Willapa Bay. These unbaited traps catch foraging crabs of all sizes. Typically, we deployed Fukui traps below the mid-intertidal, and minnow traps in high marsh vegetation such as *Spartina* and *Sciurpus*. Typically, all traps were set 10 m apart. Bait consisted of fresh frozen fish, such as cut-up carcasses of salmon, mackerel, or herring placed in commercial bait jars. Holes (0.5–1.0 cm) in the sides and lids of the containers allowed bait odours to diffuse. A single bait container with fresh bait was placed in a trap and typically left for a 24-h tidal cycle. For each trap, we noted the sex, CW, and moult stage of all crabs and recorded the presence of other bycatch. Green crabs were measured between the tips of their fifth anterio-lateral spines using digital calipers. Native crabs and other bycatch were released, but the green crabs were retained and frozen.

In Oregon and Washington, our efforts focused on six estuaries: Coos, Yaquina, Netarts, Tillamook, Willapa, and Grays Harbor (Figure 1). Further, Washington Department of Fish and Wildlife kindly provided datasets for Willapa Bay and Grays Harbor from 1998 to 2003. Estuaries were sampled from spring to autumn, total effort varying from 82 to 273 trap-days per estuary. Study sites were selected within various habitat types and tidal levels. We preferentially sampled tidal marshes, gradually sloping mudflats, and tidal channels. Green crabs are noticeably absent from the cooler, more saline mouths of estuaries, which are dominated by the larger, more aggressive red rock crab (*Cancer productus*; Hunt and Behrens Yamada, 2003). At the end of summer and in early autumn, we deployed minnow and pitfall traps to document the arrival of young-of-the-year crabs. Young crabs are easily distinguishable from older crabs by their green colouration and small size (typically 30–55 mm CW). As green crabs are still rare in Oregon and Washington, we do not detect the young-of-the-year-crabs until they are large enough to enter traps. The only time we picked up crabs as small as 14 mm CW was in June 1998, immediately after settlement of the strong *El Niño* cohort.

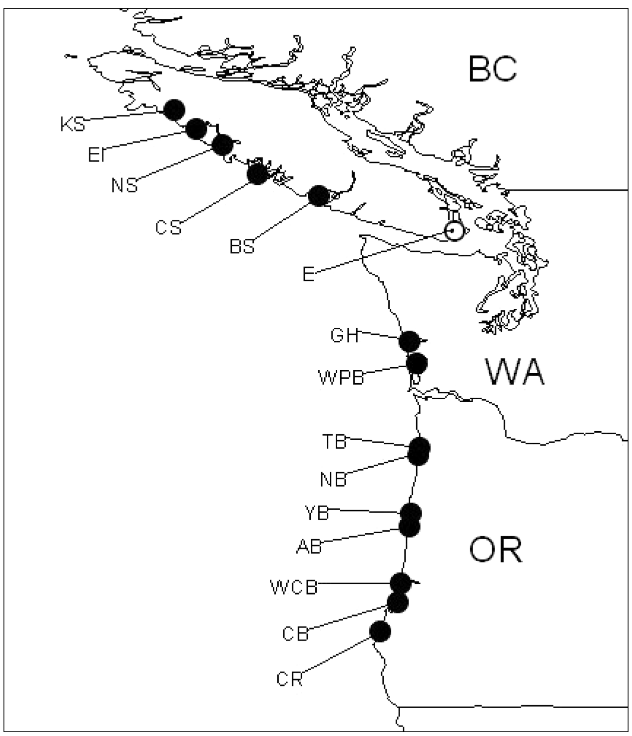

Figure 1 Major study sites of *Carcinus maenas* in British Columbia (BC), Washington (WA), and Oregon (OR), 1998–2006. Sites are listed from north to south: KS, Kyuquot Sound; EI, Esperanza Inlet; NS, Nootka Sound; CS, Clayoquot Sound; BS, Barkley Sound; E, Esquimalt; GH, Grays Harbor; WPB, Willapa Bay; TB, Tillamook Bay; NB, Netarts Bay; YB, Yaquina Bay; AB, Alsea Bay; WCB, Winchester Bay; CB, Coos Bay; CR, Coquille River. The large dots are the locations of green crab capture 1998–2006; the open circle for Esquimalt indicates a single crab caught in 1999.

In British Columbia, trap surveys were conducted on selected beaches on the west coast of Vancouver Island, Johnstone Strait, Desolation Sound, and Discovery Passage in spring and summer 2006 (Figure 1; Gillespie *et al*., 2007). Survey locations were determined in advance through examination of charts and consideration of local knowledge. Fukui fish traps were deployed on groundlines at ∼10 m spacing with a weight at one end and a float on the other end of the line. By setting and retrieving the traps from a skiff at high tide, we were able to sample muddy habitats. Traps were generally set in the intertidal, but occasionally were set in the shallow subtidal, 1–2 m below Chart Datum. Some 90–205 traps were set per site, and 5–9 sites were sampled in each embayment or region.

Age-class analysis

A growth study, based on the 1998 cohort of *C. maenas* from Oregon, Washington, and British Columbia, served as a guide for assigning crabs to year classes (Behrens Yamada *et al*., 2005). For example, male crabs captured in British Columbia in June that were between 40 and 70 mm CW were assigned to the 2005 year class, and those >70 mm were assigned to an older age class. Females were assigned to the 2005 year class if they were between 40 and 65 mm CW, and to the older age class if they were >65 mm.

Results

Distribution in space and time

In 2006, green crabs were caught in coastal Oregon and Washington estuaries, and at most sites sampled on the west coast of Vancouver Island (Table 1, Figure 1). Green crabs were captured at three of five sites in Barkley Sound, four of nine sites in Clayoquot Sound, and 7 of 12 sites in Nootka/Esperanza. Overall catch rates by area ranged from an average of 0.20 crabs trap-day^{-1} in Clayoquot Sound to 1.72 crabs trap-day^{-1} in Barkley Sound. Sites with the greatest abundance were Pipestem Inlet (2.28 crabs trap-day^{-1}) in Barkley Sound and Pretty Girl Cove (1.42 crabs trap-day^{-1}) in Clayoquot Sound. Catches in Oregon and Washington were lower, ranging from 0.02 crabs trap-day^{-1} in Grays Harbor to 0.57 crabs trap-day^{-1} in Netarts Bay (Table 1). The overall sex ratio for all our study sites was 70% males. Females are less likely to enter traps after their first year of life (Behrens Yamada *et al*., 2005).

Surveys in Johnstone Strait, Desolation Sound, and Discovery Passage, as well as limited sampling at Sooke and Saanich Inlet, did not reveal evidence of green crabs in inside waters. Likewise, trained volunteers have not yet found green crabs at any of 80 sampling sites in Puget Sound (A. Eissinger, pers. comm.). Thus far, only one green crab has been recovered near Esquimalt on southern Vancouver Island in 1999 (Table 1), but subsequent surveys by SBY, Camosun College students, and Fisheries and Oceans Canada failed to discover green crabs there.

Historical catch and sighting data by embayment reveal that green crabs have persisted past the 6-year lifespan of the colonists that arrived as larvae during the last strong *El Niño* of 1997/1998 (Table 1). Further, there has been a strong downward trend in abundance in Oregon and Washington between 1998 and 2002 as the 1998 year class started to die. This downward trend continued for Willapa Bay and Yaquina Bay until early summer 2005, but has reversed since then. Relative abundance of young-of-the-year crabs in Oregon estuaries and Willapa Bay suggests that

Table 1. *Carcinus maenas* catch rates (crabs per 100 trap-days) by embayment in the Pacific Northwest, 1997 – 2006.

Embayment	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Kyuquot Sound, BC						P			P	53
Esperanza Inlet, BC					P	P	P		5	46
Nootka Sound, BC				P						3[a]
Clayoquot Sound, BC				P						20
Barkley Sound, BC			P						P	172
Esquimalt, BC			P							
Grays Harbour, WA		28	3	3	1	<1			2	2
Willapa Bay, WA		35	43	4	3	4	3	3	25	8
Tillamook Bay, OR	P[b]	128	P	P	2[a]	3	9	8	11	28
Netarts Bay, OR	P	139			6[a]	0	25	31	49	57
Yaquina Bay, OR	P	192	69	63	57	15	6	3	13	23
Alsea Bay, OR		P				P	P			
Winchester Bay, OR		P								
Coos Bay, OR	<1	65	38	P	63[a]	5	7	13	4	8
Coquille River, OR		P							5[a]	

[a]Denotes <50 traps deployed.
[b]P indicates confirmed presence from public reports.

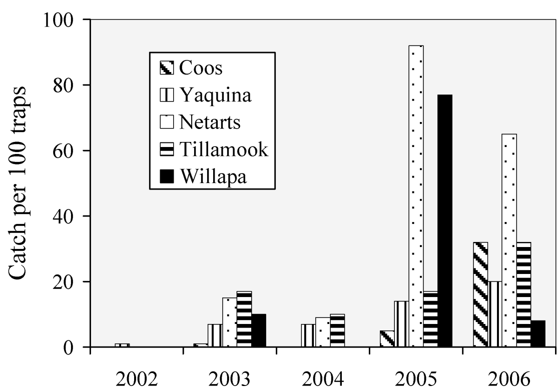

Figure 2 Relative abundance of young-of-the-year *Carcinus maenas* at the end of their first growing season.

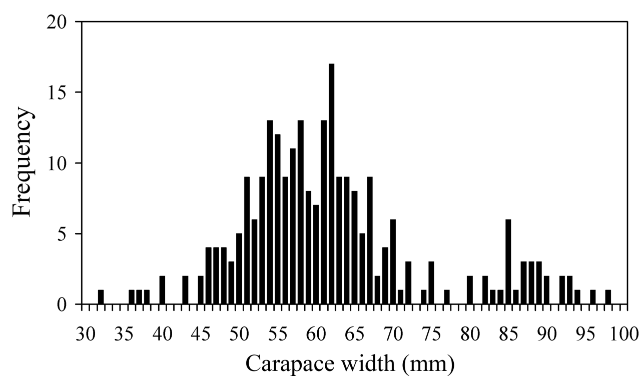

Figure 3 Carapace width (CW) frequencies of male *Carcinus maenas* collected in British Columbia, May – July 2006.

recruitment was poor for the first 4 years following the 1997/1998 colonization (Figure 2), but increases in the abundance of young-of-the-year were observed at the end of the 2003, 2005, and 2006 growing seasons (Figure 2; Behrens Yamada and Randall, 2006). Of the six coastal Oregon and Washington estuaries, Yaquina and Netarts, in the middle of the range, consistently exhibited higher recruitment of young crabs and total densities than Coos Bay and Grays Harbor, at the periphery of the range (Table 1, Figure 2).

Age structure

Size distribution in 2006 for all British Columbia sites ranged from 32 to 98 mm CW for males (Figure 3) and 29 to 76 mm CW for females. The female distribution has been broadly unimodal, centred on 55 mm CW, whereas the male distribution was bimodal with peaks between 45 mm and 70 mm and between 80 mm and 90 mm CW. As recruitment was poor in Oregon and Washington in 2002 and 2004 (Figure 2), we interpret the two peaks to represent primarily the 2003 and 2005 year classes. In British Columbia, where sampling stopped in July, 84% of the green crabs were assigned to the 2005 year class. The size distribution was similar in Oregon and Washington early that summer, but between August and October, new recruits arrived and constituted 46% of all green crabs trapped in Oregon and Washington in 2006. Overall, >85% of the crabs in the Pacific Northwest belong to the 2005 and 2006 year classes, suggesting that this young population will provide a source of larvae at least until 2012.

Discussion

Green crabs have persisted in Oregon and Washington coastal estuaries and in inlets on the west coast of Vancouver Island beyond the lifespan of the first colonizing 1997/1998 cohort. Although *El Niño*-mediated northern range expansions of marine invertebrates and fish with planktonic larvae are common, they are typically followed by range contractions once the favourable environmental conditions cease and no further recruits arrive to maintain the expatriate populations (Schoener and Fluharty, 1985). For example, the mole crab (*Emerita analoga*) occasionally establishes ephemeral populations on the west coast of Vancouver Island when larvae drift north from populations during *El Niño* years (Austin, 2000). Those populations persist for a few years, then disappear until the next incursion of larvae through northward transport. The striped shore crab (*Pachygrapsus crassipes*) is rare north of Oregon, but became quite abundant at Bamfield in Barkley Sound immediately following the 1997/1998 *El Niño*. In recent years, however, it has disappeared completely from the area (E. G. Boulding, pers. comm.). As no strong *El Niño* event has occurred since 1997/1998, it was predicted that green crabs would likewise become extinct in the Pacific Northwest once the colonizing year class had reached the end of its lifespan of ~6 years. This did not happen. Some green crabs recruited subsequently to Oregon and Washington estuaries in most years, and recruitment was fairly good in 2003, 2005, and 2006 (Behrens Yamada and Randall, 2006). The good recruitment years are linked to warmer water during the preceding winters and favourable currents in March and April for larvae to be transported back to shore (SBY and P. M. Kosro, unpublished data). A link between warm winters and good green crab recruitment has also been observed in Europe and Maine (Berrill, 1982; Beukema, 1991).

Where do the recruits have their origin? Although it is possible for larvae of green crabs to be transported several hundred kilometres north during winter and early spring of non-*El Niño* years, there were not sufficient adult green crabs in Humboldt Bay in northern California to seed Oregon estuaries (E. D. Grosholz and S. Schlosser, pers. comm.). Local recruitment is therefore a likely explanation. We have observed crabs mating in the field in early July in Barkley Sound and in late September after being trapped in Netarts Bay. Gravid females rarely enter traps, but over the years, we have observed some gravid females as early as November and as late as June. When female green crabs have been held in the laboratory during autumn, they have released eggs in November and early December and produced viable larvae in mid-February. It therefore appears that green crabs in Oregon, Washington, and British Columbia are already primarily self-maintaining and that physical and biological conditions are favourable for the species to complete its life cycle in the Pacific Northwest (Behrens Yamada, 2001).

Although average green crab abundance in the Pacific Northwest is still low, there is reason for concern. Maximum densities at some study sites in Barkley Sound have reached ten per trap, and these densities could increase if winters remain mild. To date, however, there is no evidence of green crab populations from inside waters of the Strait of Georgia, Johnstone Strait, and Puget Sound. Although currents on the open west coast of North America have been the dominant mechanism of spread, anthropogenic transport could play a role in accelerating the spread into this inland sea. The shores consist of many wave-protected bays, lagoons, and mudflats, where green crabs could thrive, and once a satellite population is established, the crabs could spread quickly through natural larval dispersal, as has happened for other invasives, including Japanese oysters (*Crassostrea gigas*), Manila clams (*Venerupis philippinarum*), and varnish clams (*Nuttallia obscurata*; Quayle, 1964; Gillespie *et al*., 2001). It is therefore important that introduction into these waters via shellfish transport, ballast water discharge, boat traffic, or other means is prevented.

In conclusion, it is clear that *C. maenas* has established local breeding populations in Oregon and Washington coastal estuaries and inlets on the west coast of Vancouver Island. Animals can live at least 6 years, so a strong recruitment is required at least once every 5 years to maintain viable populations (Behrens Yamada and Randall, 2006). The detection of strong 2005 and 2006 cohorts ensures a larval source through 2012, and if winters remain mild and green crabs continue to recruit well, it is highly likely that they will spread to northern British Columbia and Alaska. We predict that green crabs will be most abundant in shallow, wave-protected bays, where water temperatures rise well above 11°C in summer, salinity is low, and large predatory crabs, such as *C. productus*, are scarce.

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