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Continued absence of sabellid fan worms (*Terebrasabella heterouncinata*) among intertidal gastropods at a site of eradication in California, USA

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Reaching a conclusion that a non-indigenous species is truly absent following an eradication process requires sampling at relevant spatial and temporal scales. The South African gastropod shell-dwelling sabellid polychaete *Terebrasabella heterouncinata* became locally established within abalone farms in California, USA in the mid-1990s and among turban snails *Chlorostoma* (*Tegula)* spp. in the intertidal discharge zone outside one farm. An eradication program was developed and implemented in the farm discharge zone in 1996 by reducing local host density, and sampling during 1998 detected no sabellids. We conducted nine thorough follow-up surveys annually from 2001 to 2009 (mean 1,738 shells per annum, $N = 15{,}647$) and found no sabellids present at the farm discharge location. It appears that the sabellid worm has been eradicated from this site despite the continued abundance of hosts. These data provide confirmation of the successful application of the host-density threshold approach to achieving eradication of a host-dependent invasive species.

Key words: abalone, eradication *Haliotis rufescens,* invasive species, sabellid, *Terebrasabella heterouncinata*

Invasive species with a high dependence on a specific host or suite of hosts have population dynamics similar to those of classic infectious disease agents, and in some cases epidemiological theory can be applied toward their management. Culver and Kuris (2000) applied such theory to eradicate a localized infestation of the South African sabellid

polychaete *Terebrasabella heterouncinata* that was accidentally imported to California along with a shipment of abalone *(Haliotis)* intended for research. The worms live in tubes within shells of gastropods. They have a unique life history in which larvae crawl away from an adult brood chamber and settle on the shell margin of the same or a nearby abalone, or other susceptible gastropod, and secrete a mucus tube (Oakes and Fields 1996, Culver et al. 1997, Fitzhugh and Rouse 1999, Kuris and Culver 1999). The gastropod lays shell material over the nascent tube, creating a permanent burrow and the worm then metamorphoses into the adult form with a tentacular feeding crown. When brought to California it was inadvertently spread into production units at a large farm in Cayucos, San Luis Obispo County, California that raises native red abalone (*H. rufescens)*. That farm provided seed animals for abalone farms throughout the state and the worm spread to many facilities. The worm reached such high densities that the farmed abalone exhibited brittle, distorted shells and slow growth rates, resulting in animals that had very poor market acceptance (Oakes and Fields 1996). Several farms went bankrupt and most of those that remained suffered severe hardship (J. D. Moore, California Department of Fish and Wildlife (CDFW), unpublished observations 1997–2000; Culver and Kuris 2002). The sabellid infestation was successfully managed on farms by improving hygienic practices (Culver et al. 1997, Culver and Kuris 2002, Moore et al. 2007).

Inspection of non-haliotid gastropods in production units and drains at sabellid-positive abalone farms, as well as laboratory studies, showed that numerous species are susceptible, at least under intensive exposure (Kuris and Culver 1999, Culver and Kuris 2004, Moore et al. 2007). Further, inspection of the intertidal zone near the outfall of a farm in Cayucos in 1996 indicated that the sabellid appeared to have become established in a population of susceptible gastropods (predominantly *Chlorostoma* (*Tegula)* spp.; Culver and Kuris 2000).

The concept of host density threshold maintains that a pathogen will be eliminated from a host population if the hosts reach a critical low density that reduces transmission below a sustainable level (McKendrick 1940, Stiven 1968). Therefore, the pathogen can be eliminated while some hosts are still present. Based on that concept Culver and Kuris, along with abalone farmers, resource managers and volunteers, removed 1.6 million snails from the region around the outfall of the Cayucos farm during 1996, in conjunction with reducing the release of worms from the farm and removal of infested abalone and infested shell debris. Follow-up surveys during 1998 showed an absence of sabellids, suggesting that the established population had been eradicated (Culver and Kuris 2000). However, Culver and Kuris (2000) cautioned that they termed the eradication 'apparent' and recognized the possibility that the sabellid infestation could remain at an undetectable level over their sampling period, and noted that it is extremely important to continue monitoring in subsequent years. Indeed, the potential continued presence of the worm can only be discredited by sampling at relevant temporal and spatial scales. Therefore, we began formal monitoring of the site in 2001, and concluded the eradication successful in 2009 following nine years of negative findings.

Materials and Methods

We collected gastropods from the Cayucos eradication site annually at low tides using a modification of the six transects of Culver and Kuris (2000) (Figure 1). The transect

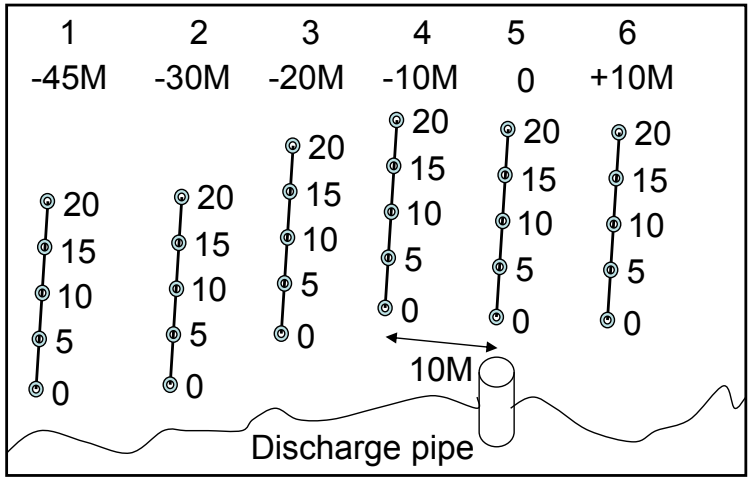

Figure 1.—Schematic diagram showing locations of transects and transect sampling points relative to the discharge pipe from a land-based abalone farm in Cayucos, San Luis Obispo County, California, USA, 2001-2009. The upper number indicates the transect number; the number below it indicates distance from the discharge point. Negative numbers are south of the discharge pipe and the positive number is north.

locations were similar to those reported by Culver and Kuris (2000), but we collected samples along each point on the transect line at 0, 5, 10, 15, and 20 m away from shore. One transect line was directly offshore from the discharge pipe, four were to the south and one was to the north. This asymmetric design was selected by Culver and Kuris (2000) due to prevailing southerly currents. Collections targeted 60 live adult snails (*Chlorostoma* spp.; minimum shell size of approximately 10 mm) per transect point. The sample size of 60 allowed for detection of a pest, pathogen or condition with 95% confidence if its prevalence in the population is at least 5% (USFWS and AFS-FHS 2003), assuming 100% efficiency of the diagnostic method (i.e., any sabellids present in the samples will be detected). The area around each transect point was searched in increasingly wide circles up to a radius of 2.5 m. When live snails were not present in sufficient quantity we collected empty *Chlorostoma* shells or shells with hermit crabs, and very small amounts of other gastropods (primarily *Nucella* sp. and various limpets). When several minutes went by without finding any new gastropods or gastropod shells, sampling of the transect point was considered complete for that sampling date. For reasons that were not recorded, the 0-m stations (i.e. the starting stations on each transect) were not surveyed in 2001-2002.

Shells from each transect point were held in separate labeled bags in a -20° C freezer and later examined for the presence of sabellid tubes, either by viewing under a dissecting microscope, or viewing without magnification that was followed by careful observation of any suspect shells under a dissecting microscope. Examiners were specifically trained in the identification of sabellids on gastropod shells.

Results

During the nine sampling events from 2001 to 2009 we collected a total of 15,647 snails with an average of 60.7 per transect point (0, 5, 10, 15, and 20 M from shore) per year

for each of the six transects (Table 1, Table 2). The majority were *Chlorostoma funebralis* with the remainder being largely *C. brunnea;* these two species comprised 93.4% of the snails examined. The stations closer to shore typically had an excess of *C. funebralis*, and 60 individuals could be collected within a few minutes. The outer and, therefore, generally deeper stations had few *C. funebralis*, with *C. brunnea* being the predominant gastropod, but occurring at much lower density than *C. funebralis* closer to shore. These deeper stations required greater search efforts, often in surfgrass habitat. No sabellids were detected among any of the snails examined.

Table 1.— Total gastropod shells examined annually by transect number at Cayucos, San Luis Obispo County, California, USA, 2001–2009.

	Transect #						
Date	1	2	3	4	5	6	Totals
6/25/2001	206	185	253	197	219	195	1255
6/12/2002	300	282	316	265	240	240	1643
8/28/2003	316	321	317	318	321	327	1920
8/2/2004	300	300	301	300	300	300	1801
5/25/2005	312	310	320	309	318	321	1890
4/20/2006	314	320	335	338	332	262	1901
3/15/2007	198	251	232	282	319	312	1594
4/9/2008	188	234	277	325	320	293	1637
4/27/2009	322	337	326	363	332	326	2006
Totals	2456	2540	2677	2697	2701	2576	15647

Table 2.— Total gastropod shells examined annually by transect station (distance from transect point closest to shore, 0-m) at Cayucos, San Luis Obispo County, California, USA, 2001–2009.

	Transect Station					
Date	0	5-m	10-m	15-m	20-m	Totals
6/25/2001	n.d.	360	336	313	246	1255
6/12/2002	n.d.	387	476	387	393	1643
8/28/2003	383	383	391	386	377	1920
8/2/2004	360	360	360	360	361	1801
5/25/2005	383	380	380	379	368	1890
4/20/2006	391	399	395	394	322	1901
3/15/2007	374	363	350	279	228	1594
4/9/2008	388	386	330	296	237	1637
4/27/2009	421	406	399	387	393	2006
Totals	2700	3424	3417	3181	2925	15647

Discussion

Decisions on how to address non-native species introductions are complex and whether to devote resources toward a rapid response, and how much to invest in the response, are often controversial (Myers et al. 2000, Locke and Hanson 2009). The sabellid eradication at Cayucos has been cited as a case of successful eradication of a marine invasive species (e.g., Myers et al. 2000, Williams and Grosholz 2008, Locke and Hanson 2009), often with discussion regarding the characteristics of the system and responses that allowed success. Among these are: (1) reduction of the infestation source by installing screens in the outfall stream to catch shell and shell debris; (2) the requirement of live gastropod hosts in the life cycle; (3) the limited dispersal of the larval stage; (4) a rapid response; and (5) coordination among industry, academia and regulators. Additionally, the most abundant host in the Cayucos intertidal, *C. funebralis*, is a less susceptible host than the red abalone (Moore et al. 2007).

In their report following the density reduction of *Chlorostoma* spp. from the Cayucos site, Culver and Kuris (2000) stated that their efforts appeared to have eradicated the sabellid at the Cayucos outfall site, but emphasized the need for continued monitoring for many years following their report. The transects used by Culver and Kuris (2000) provided an appropriate spatial scale of sampling and we concluded that our annual surveys provided an appropriate temporal scale, given known sabellid life cycle and longevity (Fitzhugh and Rouse 1999), including a 165-day generation time at 15.6° C (Finley et al. 2001). Ninety-five percent of our samples contained at least 55 animals; it is worth noting, however, that at the twelve transect points with fewer animals, the risk of sabellid presence is lower than at other, higher-density transect points.

No effort has been made to determine if there was any detrimental impact as a result of the removal of 1.6 million *Chlorostoma* in 1996, or our removal of nearly 16,000 snails in subsequent years. However, we found the snails to be extremely abundant at most transect points during our initial efforts in 2001 and noted no consistent changes in abundance in subsequent years. Recruitment of juveniles from pelagic larvae or migration of juveniles and adults from adjacent areas, or both, likely tempered the focal population reductions.

The population of sabellids on the farm at Cayucos peaked in approximately 1996 and then rapidly declined as new husbandry practices allowed for the production of sabellid-free abalone as the remaining infested groups were sold off. A few infested individuals were detected sporadically at the farm through 2004 (J. D. Moore, CDFG, 2004 unpublished data). None have been detected since then, and the farm was certified by the California Department of Fish and Game (CDFG) as sabellid-free in 2008. Thus it appears that the Cayucos intertidal site no longer has sabellids present and there is negligible chance of re-infestation. The Cayucos outfall site is the only location where sabellids are known to have become established in California. Intertidal surveys of outfall areas of onshore abalone farms in the mid-1990s (Culver and Kuris 2002) and a snapshot survey of 24 exposed sites conducted by us during 2002-2006 revealed no sabellid infestations (Moore et al. 2007).

This study confirms the success of the eradication approach taken by Culver and Kuris, based on the concept of host-density threshold (McKendrick 1940, Stiven 1968). The Cayucos eradication is an apparently unique example of the application of epidemiological theory toward eliminating a marine invasive species, although this approach is consistent with recent eradication theory and practices recognizing that localized pest extinctions can be accomplished without 100% removal. Liebhold and Bascompte (2003) provided extinction

modeling and real-world data on control of gypsy moth expansion in North America. They emphasized three points: (1) extinction can be achieved with less than 100% population reduction due to stochasticity or Allee dynamics, or a combination of the two; (2) there is always a stochastic component to population extinction and, therefore, eradication should be viewed in a probabilistic framework; and (3) the proportion of the population removed is critically important, and rapid response following detection is highly desirable. These ideas, and the successful eradication of *Terebrasabella heterouncinata* at Cayucos, provide further justification for non-indigenous marine species surveillance programs and rapid-response planning efforts.

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