A REVIEW OF U.S. PACIFIC COAST KRILL

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Principal stocks of interest

Eight species of euphausiid shrimp form the bulk of the euphausiid community in the Transition Zone of the California Current System (Brinton and Townsend 2003), but only two cold-water species, *Euphausia pacifica* and *Thysanoessa spinifera*, form large, dense surface aggregations and are likely to be potential fishery targets. They are also the most commonly reported euphausiids reported in the diets of a wide variety of California Current seabird, marine mammal and fish species (see Importance as Forage section below).

The daytime near-surface aggregating behavior of *E. pacifica* and *T. spinifera* is well known, and has been documented by Boden et al. (1955), Barham (1956), Pearcy and Hosie (1985), Smith and Adams (1988), and others. The sub-tropical and marginally tropical *Nyctiphanes simplex* also occurs in the California Current, and aggregates at the surface in large swarms, but is only abundant in U.S. West Coast waters during strong El Niño years, occurring predominantly to the south in Mexico waters (Brinton and Townsend 2003). Another euphausiid, *Nematocelis difficilis* is very abundant in the California Current, but not a vertical migrator, preferring the deeper layers of the thermocline where it is less accessible to harvest than *E. pacifica* and *T. spinifera*. The remaining species, *T. gregaria*, *E. recurva*, *E. gibboides*, *E. eximia*, are less abundant and not likely candidates for exploitation.

Biology

E. pacifica ranges throughout the subarctic Pacific, including the Gulf of Alaska as far south as 25 °N latitude (Brinton 1981). It performs extensive vertical migrations, usually over depths greater than 200 m, although it also occurs over the shelf. Off California, the adults live at a daytime depth of 200-400 m rising to near the surface at night (Brinton, 1976; Youngbluth 1976), sometimes amassing near the surface during the day (Endo et al. 1985; Brinton and Townsend 1991). *T. spinifera*, which commonly forms daytime surface swarms, is more coastal, occurring in neritic water mainly less than 100 m deep. It occurs from the southeastern Bering Sea south to northern Baja California, with regions of high density associated with centers of upwelling (Boden et al. 1955; Brinton 1962). Both are grazers on microscopic plants and animals. *E. pacifica* usually reaches its maximum length of 22 mm in about 12 or 13 months, have about a one-year life expectancy in our region, and individuals from 10 to 15 mm carapace length tend to predominate in the population. *E. pacifica* appears to have continuous recruitment year round with peaks associated with upwelling periods (Brinton 1976). Under ideal conditions a female, which carries 20-250 eggs which hatch into larvae, could spawn every two months.

The larger *T. spinifera* (to 30 mm) is thought to have a three-year life cycle, and a discrete spawning season that extends from May to July off California, coincident with the strongest upwelling (Brinton 1981). From May to July, it forms extensive inshore surface swarms as fully

mature adults during the peak of the upwelling season (Brinton 1981, Smith and Adams 1988). These adults are thought to swarm, breed, then presumably die at the end of their three-year life cycle (Nemoto 1957). Maturing subadults are also know to swarm near the surface in late summer and fall (Schoenherr 1991; Kieckhefer 1992; Fiedler et al. 1998). Compared to other California Current euphausiids, adults and large juveniles of this species are thought to be more mobile and adept at avoiding towed nets, and thus likely to be underestimated when extrapolating abundance from net tows (Brinton 1965; Smith and Adams 1998; and Brinton and Townsend 2003).

Population dynamics

No comprehensive overall biomass estimates for any krill species have been made for the California Current area off the U.S. Pacific Coast, and MSY and OY are unknown. Brinton (1976) has described the population biology of *E. pacifica* off southern California with respect to reproduction, growth and development of cohorts, and successions in population structure and biomass over a four year period (1953-56). In a 1983 NMFS guide to underutilized fisheries resources off California, population size of *E. pacifica* was roughly estimated at 'probably over 100 million tons in California,' possibly based on Brinton's (1976) work and known distribution off California, although no supporting data are provided.

Brinton and Townsend (2003), using the CalCOFI data series, recently published a time series analysis of fluctuations in abundance of the major California Current euphausiid species in relation to decadal oceanographic variability over the last 52 years. They found cold-water *E. pacifica* and *T. spinifera* declined dramatically during extreme warm water events, although they appear to be quite resilient in their ability to rebound from these periods of unfavorable oceanographic conditions. The two species abundances in southern and central California varied similarly over the five survey decades, both experiencing marked post-El Niño recoveries once cooler water periods returned. Periods of population depletion became increasingly frequent, though irregular, after a cool water regime shifted to a warm water regime in the 1970s. The more numerically abundant *E. pacifica* uniformly collapsed by as much as 90% during warm-water El Niño periods, but recovered to irregular but distinct bi-decadal peaks in abundance during six strong cold-water La Niña episodes, including the most recent cool-water episode from 1999 through at least spring 2002.

Importance as Forage

Diet studies over the last forty years indicate that krill are an integral part of the California Current System food web. *Euphausia pacifica* and/or *Thysanoessa spinifera* are preyed upon by market squid, *Lolling opalescen*s; Pacific hake, *Merluccius productus*; Pacific herring, *Clupea harengus*; dogfish, *Squalus acanthias*; blue shark, *Prionace glauca*; sablefish, *Anoplopoma fimbria*; myctophids (family: Myctophidae); jack mackerel, *Trachurus symmetricus*; various juvenile and adult rockfishes, *Sebastes* spp., which prey on eggs, larvae and adult krill; various flatfishes (e.g., Pacific sanddab, *Citharichthys sordidus*, slender sole, *Lyopsetta exilis*; Pacific halibut, *Hypoglossus stenolepis)*; Pacific salmon (*Oncorhynchus* spp.), albacore, *Thunnus alalunga*; humpback whale, *Megaptera novaeangliae*; blue whale, *Balaenoptera musculus*; Grey whale, *Eschrichtius robustus*; and various seabirds, especially Cassin's auklets, *Ptychoramphus*

aleuticus; sooty shearwater, *Puffinus griseus*; and common murre *Uria aalge* (Phillips 1964; Alversen and Larkins 1969; Alton and Nelson 1970; Pinkas et al. 1971; Cailliet 1972; Manuwal 1974; Tyler and Pearcy 1975; Baltz and Morejohn 1977; Karpov and Cailliet 1978; McCall et al. 1980; Vermeer 1981; Chu 1982; Peterson et al. 1982; Livingston 1983; Lorz et al. 1983; Brodeur and Pearcy 1984; Briggs et al. 1988; Chess et al. 1988; Smith and Adams 1988; Ainley and Boekelheide 1990; Ainley et al. 1990; Kiekeffer 1992; Reilley et al. 1992;Tanasichuk 1995; Ware and McFarlane 1995; Ainley et al. 1996; Robinson 2000; Benson et al. 2002; Hewitt and Lipsky 2002). Hake and Cassin's auklet appear so dependent on these species for food that the distributions of euphausiids determine those for hake and auklets (Vermeer 1981; Tanasichuk 1995; Ainley et al. 1996; Briggs et al. 1988). Krill are also especially important food of salmon, preparatory to their ascending tributaries to spawn. When the rust-colored swarms appear off central California, commercial sport fishing boats, guided by flocks of feeding seabirds, seek krill swarms out in search of salmon, which feed heavily on krill from April to July (Smith and Adams 1988). Blue and humpback whales also converge on krill-rich upwelling centers such as around the Farallon Islands, Monterey Bay, and the Point Conception/Channel Islands area to feed on *T. spinfera* and *E. pacifica* during summer and fall, since at least the mid-1980s and early 1990s (Smith and Adams 1988; Schoenherr 1991; Fiedler et al. 1998, Croll et al. 1998).

Commercial Importance

There is a market for krill as food for aquarium fish, in fish culture operations, and for pet food. It is also marketed for human consumption in non-domestic markets. It is most often frozen, and sometimes freeze-dried for ease in handling and distribution to retail markets (NMFS 1983). The British Columbia euphausiid fishery is market-limited with the majority of the product being frozen for export to the US where it is used in the production of fish feed or pet food (Nicol and Endo 1997).

EXISTING AND POTENTIAL KRILL FISHERIES—U.S.-CANADA PACIFIC COAST

California

California imposed a ban on krill fishing in state waters in 2000.

Oregon

Oregon imposed a ban on krill fishing in state waters in 2003. Fishing beyond state waters may not be feasible because of rough ocean fishing conditions which constrain krill fishing operations.

Washington

Currently, no krill fishery takes place in Washington, and there has been no interest expressed in harvesting krill in state waters. Washington law prohibits the landing and sale of commercial quantities of krill, which is designated an unclassified species with very limited take options. Given recent discussions relating to krill harvest in other Pacific coast areas, the state may consider additional modifications that might make future commercial harvest of krill in

Washington even more unlikely.

British Columbia

The only krill fishery along the U.S.-Canada Pacific Coast exists in the Strait of Georgia, British Columbia (Fulton and Le Brasseur 1984; Nicol and Endo 1997). A fishery for *E. pacifica* also exists in Japan in the western Pacific (Endo 1995; Nicol and Endo 1997).

Information on the British Columbia fishery has been summarized by Nicol and Endo (1997). It began on a experimental basis in 1972, confined to the Strait of Georgia and the east coast of Vancouver Island. Quotas were established in 1976 in response to concerns about harvesting such an important forage species upon which salmon and other commercially important finfish depend. The annual catch was set at 500 t with an open season from November to March to minimize the incidental catch of larval and juvenile fish and shellfish. This quota was derived from an estimate of the annual consumption of euphausiids by all predator species in the Strait of Georgia, and is 3% of this estimate. In 1983, participation in this fishery was restricted to those individuals who had applied for, and held, a certain category license, which was not subject to limited entry. Until 1985, annual landings were less than 200 t, with fishing concentrated initially in Saanich Inlet, then Howe Sound and most recently in Jervis Inlet. Due to continued concentration of fishing effort in Jervis Inlet rather than the adjacent waters in the Strait of Georgia, separate inlet quotas were introduced in 1989. The annual TAC increased to 785 t; 500 t for the Strait of Georgia and 20 to 75 t for each of the major mainland inlets.

In 1990, due to concerns of local stock overfishing, the overall annual quota was reduced again to 500 t; 285 t for the mainland inlets and 215 t for the Strait of Georgia. That year, 56 licenses were issued, of which 17 reported landings of 530 t for a landed value of Can $415,000. This was the first year since the beginning of this fishery that the annual quota had been reached. Only 53 t of euphausiids were reported landed in 1993 with a total landed value of Can $41,000. This decline in landings from 381 t reported in 1992 was a function of market conditions rather than any decline in krill stocks. Preliminary landings of euphausiids reported for 1994 were in excess of 300 t, with a value of Can$ 259,000, as markets stabilized somewhat from the previous year. The number of licenses issued for this fishery increased annually from 7 in 1983 to 56 in 1990, then declined to 45 in 1991. In 1993, licenses were limited to 25 vessels upon the advice of industry and because the annual quota was being taken by the current fleet. Only one vessel during 1993 and three vessels during 1994 reported euphausiid landings. Bycatch consists of larval and juvenile fish and myctophids (Lee 1995).

In late 1995 a workshop was held at the University of British Columbia on "Harvesting Krill: Ecological Impact, Assessment, Products and Markets " (Pitcher and Chuenpagdee 1995). The workshop dealt in some detail with the British Columbia euphausiid fishery, the importance of euphausiids to the coastal marine ecosystem, and improvements in assessments methods of the potential yield of British Columbia krill stocks. The Regional Executive Committee of the Canadian Department of Fisheries and Oceans has stated that as a matter of policy the region is not prepared to support additional developmental fisheries on forage species such as krill, and the 500 t quota for the Strait of Georgia and mainland inlets is expected to remain fixed for the foreseeable future (Morrison 1995).

Fishing methods-British Columbia

In the British Columbia fishery, two types of vessels participate — smaller freezer vessels whose catches are limited due to freezing capacity (5-6 t of krill a day) and larger vessels that land large quantities of euphausiids for onshore processing and freezing (Nicol and Endo 1997). The catch must be frozen within 24 hrs to avoid a significant deterioration of product quality. The fishing season can be as short as 20 days (actual fishing days) and individual vessels may land as little as 32 t in a season. Nets used have mouth areas of around 80 m^2, the trawl mouth is kept open by means of a beam and is buoyed to keep it from flipping when the ship turns. There are weights on the footline to maintain the net's shape. Fishing is carried out close to the surface - often less than 20 m deep and on moonless nights when the krill rise to the surface forming layers less than 10 m in vertical extent. The krill are located by echosounders. The larger vessels use a seine net and are usually out-of-season salmon fishing boats with no onboard freezing capacity. The presence of these vessels in the fishery is usually dependent on the success of the salmon fishery. If there has been a bad salmon catch, then krill are fished to increase revenues.

CALIFORNIA DATA SOURCES FOR CALIFORNIA CURRENT KRILL

NMFS SWFSC La Jolla Laboratory and University of California

SIO CalCOFI Euphausiid data sets: These consist of data generated from over 3,000 plankton samples collected in the California Current area (predominantly off southern and central California) since 1950 by California Cooperative Fisheries Investigations (NMFS and State of California, UCSD Scripps Institution of Oceanography). *Sampling period*: 1950-2002. *Associated publications*: Numerous reports and publications on California Current euphausiids published by Brinton and Brinton and Townsend are based on these data. The most recent publication, Brinton and Townsend 2003, describes a long time series of fluctuations in abundance of the major California Current species over the period 1950-2002, in relation to oceanographic regimes and La Niña and El Niño events. *Contacts:* Ed Brinton, Annie Townsend, UCSD SIO

NMFS/SWFSC Whale Habitat and Prey Studies (WHAPS) data sets: Acoustic, MOCNESS net, and whale scat data collected to determine krill distribution and abundance in relation to whales in the region of the southern California Channel Islands area. *Sampling times*: August 1995; July 1996. *Associated publications*: Croll et al. 1998; Fielder et al. 1998; Armstrong and Smith 1997. *Contacts:* Paul Fiedler, David Demer, Sue Smith, NMFS SWFSC La Jolla Laboratory.

1992-1993 FORAGE (Fishery Oceanography and Groundfish Ecology) cruises data set and samples: Acoustic, hydrographic and MOCNESS net data for stations sampled between Pt. Sur and Pt Arena, California 16-26 March 1992 and 26 June-7 July 1993 FORAGE cruises. *Associated publications:* Lynn et al. 1995. *Contacts* Bill Watson, Richard Charter, Ron Lynn, Sue Smith, SWFSC La Jolla Laboratory.

NMFS SWFSC Santa Cruz Laboratory and University of California

NMFS/SWFSC Santa Cruz Rockfish Recruitment Assessment Cruise Data: Acoustic, midwater and occasionally Tucker trawl data have been collected to determine the distribution and abundance of krill along the continental shelf break between Point Reyes and Monterey Bay. Concurrent surveys of birds and marine mammals are conducted on these cruises by Point Reyes Bird Observatory staff. *Sampling dates*: Acoustic information has been gathered during annual May/June juvenile rockfish surveys since 1999. Euphausiid catch information from midwater trawls has been collected since 1983. Krill identified to species in 1980s, and since 2002 by University of California Santa Cruz researchers. Intervening years' catches (1990-2001) not identified to species. *Associated publications*: Adams 2001; Laidig, et al. 1995; Brodeur, R. D., W. G. Pearcy, and S. Ralston 2003. *Contact:* Steve Ralston, NMFS SWFSC Santa Cruz Laboratory.

Shortbelly Rockfish Prey Study Data set: Day-night depth-stratified euphausiid collections made in the area of Ascension Canyon to determine temporal and spatial distribution of euphausiid species in relation to diel feeding patterns of shortbelly rockfish. *Sampling periods*: 74 sampling days between 1979 and 1982. *Associated publications*: Chess et al. 1988. Contact: Steve Ralston; Pete Adams, NMFS SWFSC Santa Cruz Laboratory.

Chinook Salmon Prey-switching Data Set: Day-night depth-stratified euphausiid collections made in the Gulf of the Farallones to determine temporal and spatial abundance of euphausiid species in relation to the feeding patterns of the chinook salmon. *Sampling period*: From about 1985 through 1998. *Associated publication*: Smith and Adams 1988; Adams 2001; Adams, Samiere, and Ryan in prep. Contact: Steve Ralston, Pete Adams, NMFS SWFSC Santa Cruz Laboratory.

University of California Santa Cruz: Acoustic data and whale tagging data in collaboration with NMFS/SWFSC Whale Habitat and Prey Studies (see above), and regular krill surveys in Monterey Bay. *Sampling Period:* WHAPS data sets, August 1995; July 1996. Monterey Bay data sets 1997-present. *Associated publications:* Croll et al. 1998; Fielder et al.1998. *Contacts:* D. Croll, B. Marinovic, M. Mangel

Data on krill is also gathered in Washington and Oregon by:

NWFSC-Newport Laboratory and Oregon State University, Newport, OR: Associated data bases relating to biology and ecology of krill populations off Oregon and the Pacific Northwest. *Contacts:* W. T. Peterson, R. Brodeur, W.G. Pearcy.

University of Washington: Data on Puget Sound euphausiid biology and habitat requirements. *Contacts:* A. Leising and A. Dignon

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