Chapter 3. Biological Characteristics of Ballast Water in Oil Tankers

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3A. Purpose

The overall goal of this research component was to characterize the biota associated with segregated ballast water of tankers arriving to Port Valdez. For this analysis, we designed a sampling program to measure temporal (seasonal, annual) and spatial (source port) variation in the biota associated with the ballast water.

We focused primarily on the mid-large (>80 micron) zooplankton resident in the water column of ballast tanks, and present the results of this analysis here. We have included some information on the phytoplankton concentrations present in our samples, but the sampling methods (below) were not designed to characterize these organisms and many of the other taxa (e.g., bacteria, viruses, and other microorganisms) that are small in size. This choice does not imply that small organisms are not significant from an invasion standpoint, as the potential effects of toxic dinoflagellate blooms are very evident (see Introduction). Instead, we simply did not have the resources to include all taxonomic groups in our analyses.

We chose to focus on the mid-large zooplankton for multiple reasons. First, the taxonomic resolution is relatively good compared to many of the other (smaller) organisms. Second, most known NIS that are established at the source ports of oil tankers, such as San Francisco Bay, occur (for some portion of their life history) in this zooplankton community. Third, we could readily gain access to the plankton community (as opposed to the bottom sediments). Finally, the sample analysis for larger zooplankton is not as technically difficult or time consuming as that necessary for the smaller organisms, allowing us to analyze samples from a large number of ships for statistical comparisons.

The analysis of zooplankton presented here is one of the most comprehensive and quantitative studies of ballast water in the world. Additional data on the biota associated with ballast water also appear in other chapters. Our analysis of ballast water exchange (Chapter 5) includes survivorship of plankton during 8 separate voyages, effects of exchange on zooplankton, and some information on bacteria and ciliate protozoans. Biota associated with the bottom sediments of ballast tanks, as well as the hulls and seachests, are also examined (Chapters 6 and 7, respectively).

3B. Methods

3B1. Source and Number of Sampled Ships

For a 13-month period (December 1997 – December 1998, hereafter 1998), we conducted an intensive sampling program of ballast water on tankers that was stratified by source port and season. Most tankers and ballast water arriving to Port Valdez came from three U.S. domestic

port systems: Puget Sound, San Francisco Bay, and Long Beach (see Chapter 2). To characterize biota for these ports by seasons, we sampled a minimum of 3 tanker arrivals per month from each of the three domestic source port systems (i.e., 10 per quarter x 3 source ports = 30 per quarter). Although relatively few (23) tankers arrived from foreign ports in Port Valdez during this year, we sampled as many as possible (n=19) to compare the biota arriving from foreign versus domestic sources. We also sampled a limited number of arrivals from the other two domestic ports: Oregon and Hawaii (which comprised < 10% all arrivals; see Chapter 2).

In June of three consecutive years (1997, 1998, 1999), we collected samples from approximately 10 tankers arriving to Port Valdez from the domestic ports of Puget Sound, San Francisco Bay, and Long Beach. Samples from 1997 were collected as part of a Pilot Study that we conducted for RCAC (Ruiz and Hines 1997), and the samples for 1998-1999 were collected in the present study. Together, these samples were used to characterize annual variation in the ballast water biota arriving to Alaska.

3B2. Sample Collection and Analysis

We boarded and sampled tankers immediately upon their arrival to Port Valdez. As described above, we sampled approximately 2-3 vessels per week over the 13-month period. Although we attempted to collect ballast water from every tanker boarded, vessels with double bottoms could not be sampled easily without disruption of ship operations and modification of our standard sampling protocol. In the present analysis, we therefore have included primarily (but not exclusively) vessels without double bottoms.

We applied our established methods for qualitative and quantitative analysis of biota transported in ballast water, which evolved from methods developed by J.T. Carlton (e.g., Carlton and Geller, 1993; LaVoie et al.1999; Smith et al., 1999). Our protocol consisted of collecting the following information and samples:

- Ship and ballast management information: Last port of call, number of tanks by type, capacity of tanks, amount of segregated and non-segregated ballast water on board, source(s) of ballast water, age of ballast water, date of arrival, ballast management practices;
- Physical variables of ballast water: Water temperature and salinity were measured (surface and 10m depth) for each tank sampled (as below), collecting ballast water with a Niskin bottle through the Butterworth hatches; oxygen (O_2) concentration was not measured because previous extensive analysis of ballast water tanks in other cargo ships indicated that O_2 concentrations rarely varied and were not appreciably lower than saturation (Smith et al., 1996).
- Biological samples of ballast water: Plankton samples were collected by towing a standard plankton net (80 micron mesh, 30 cm diameter) vertically through the entire height of the water column in each ballast tank; access to ballast tanks was obtained through the Butterworth hatches. A single tank was sampled for each ship, when ballast water was present and accessible, and two plankton tows were collected for each tank; the height of each plankton tow was measured to the nearest 10 cm.
- Additional observations and opportunistic samples: Upon initiating sampling of ballast tanks, we routinely examined the surface waters to look for large, mobile biota (e.g., fish) and organisms attached to the sides of tanks; we often took opportunities to collect any such

organisms observed, as well as bottom sediments, since these are usually missed in our plankton tows.

- Physical variables of port water: Shipside water temperature and salinity were measured (surface and 10m depth) usually within an hour of sampling ballast water of most vessels; the samples were collected from the berth platform (within 50m of the ship), using a Niskin bottle.

Most plankton samples were returned to the laboratory at Valdez and examined initially within an hour of collection to assess condition of organisms present. More specifically, we examined each plankton sample with our dissecting microscopes (10-40x), to provide a qualitative assessment of plankton viability. Each sample was washed carefully into a finger bowl for examination, and the presence of each morphologically distinct taxonomic group was noted. For each taxon identified, the percent of individuals alive was estimated by evaluating their morphological integrity, movement, and activity; although status of some organisms (e.g., diatoms or eggs) was difficult to discern with confidence during a brief screening. After initial microscopic examination, the plankton samples were preserved in 5% buffered formalin for later identification and enumeration of organisms (as below).

We used two different methods to characterize the plankton samples, as follows:

- Coarse Analysis. All samples were characterized by Coarse Analysis, consisting of a direct count of individuals according to general taxonomic groups, usually phyla (e.g., molluscs, crustaceans, echinoderms). The minimum of number of distinctly different taxa were also estimated in Coarse Analysis of each sample.
- Fine Analysis. For a subset of samples (roughly 1/3 of the ships from domestic ports), Fine Analysis was used to enumerate all morphologically distinct taxa at the lowest taxonomic level possible. For many groups that included larval invertebrates (e.g., bivalves, gastropods), identification could not progress beyond gross taxonomic groups; further identification can only be accomplished with intensive culture of larvae to adult stages, upon which taxonomy is based, or the use of molecular probes. For other groups that include adult stages (e.g., copepods), we sought species-level identifications.

The two methods were selected to provide different types of information. The Coarse Analysis allowed us to test for patterns in the biota across all ships, increasing the statistical power of the analysis. Since many species were not present on each ship, such an approach was not feasible with finer taxonomic resolution. In contrast, the Fine Analysis allowed us to quantify the densities of particular taxa, usually crustacean groups with adult forms (see results), and test for the presence of nonindigenous species known from the source ports. These data also allow us to characterize the frequency and density of particular nonindigenous species in the ballast water.

For both analyses, samples were concentrated on an 80 micron sieve and washed into a finger bowl for identification and enumeration. Each whole sample was examined using a stereo microscope, and all morphologically distinct taxa were identified to the desired taxonomic level (as above). For abundant taxa (> 100 individuals/sample), samples were split using a Folsom plankton splitter to achieve counts between 10-100 individuals per subsample (usually splits of 1/8 to 1/32). For organisms in split samples, two subsamples were counted.

Taxonomic identification of plankton followed a standard protocol. For those groups of organisms that can be identified using the life stages present in ballast water samples (as discussed above), we made an initial identification based upon our current knowledge and literature that was immediately available to us at SERC. For many copepods, we were able to discern genera without much difficulty. Enumeration proceeded based upon the lowest discernible taxonomic units, and representative specimens were vouchered (in Fine Analysis) for taxonomic verification and, wherever possible, species-level identification. These voucher specimens were sent to taxonomists at the Smithsonian Institution's National Museum of Natural History and elsewhere for verification and identification.

3B3 Data Analysis

Throughout our analyses, we use "ship" as the level of replication within a class variable (e.g., source port, season, year), because multiple samples from the same ship are not independent of each other. Although our replicate plankton samples per ship provide some important information on variation within ships, these are not statistically independent (since the ballast water originates from the same source and time) and mainly provide greater confidence in estimating plankton communities per ship. Thus, we estimated density per ship as the mean of replicate tows.

We derive most of the results reported from the Coarse Analysis. All enumeration is also completed for the Fine Analysis, but identification of only a portion of the voucher specimens has been finished to date. Although we cannot yet discuss the frequency and density of individual taxa (as described above), we confirm the presence of numerous nonindigenous species in the Fine Analysis, and these are reported here. We will include full results of the Fine Analysis, when completed, in a future publication and provide a copy to RCAC.

Virtually all organisms collected in the ballast water samples were alive and appeared to be in good condition. Indeed, many of the organisms collected from these samples performed well in laboratory culture and experiments, as described in Chapter 4. Thus, we considered all organisms counted in fixed samples to be alive at the time of sampling.

In most of the analyses, we have excluded the chain-forming diatoms. Although we enumerated these organisms to the full extent possible, quantitative counts are particularly problematic and unreliable, because the chains break apart during sample collection and processing. We have therefore included information on their prevalence and the counts made but excluded these data from most estimates of organism densities.

Finally, the presentation of water temperature and salinity, for both the ballast water of oil tankers and Port Valdez, are presented in Chapter 4.

3C Results

Source and Number of Sampled Ships

During this study, we sampled the ballast water of 169 tankers arriving to Port Valdez (Table 3.1). Our samples included 8-15 arrivals per quarter for each of the three major domestic

ports (Puget Sound, San Francisco Bay, and Long Beach) and 3-7 arrivals per quarter from foreign ports (primarily Korea; see Chapter 2).

Table 3.1. Prevalence and densities of taxa in the ballast water arriving to Port Valdez for each source port. Shown for each taxon and source port are the prevalence, density among all ships, and density for ships only when taxon was present. Standard errors are shown in parentheses with each density measure. Source ports include: Puget Sound, WA (PS); San Francisco Bay, CA (SF); Long Beach, CA (LB); Foreign port with open-ocean exchange (EX); Columbia River, Oregon (OR); and Barbers Point, Hawaii (HI). The data include all sample dates. Sample sizes for each source port as follows: PS (n=48), SF (n=50), LB (n=46), EX (n=19), OR (n=2), HI (n=4).

				(%)	(density/m³)	
Phylum	**Taxa**	**source**	**n**	**Prevalence**	**mean(se) all ships**	**mean(se) when present**
DINOFLAGELLATA						
		PS	48	88	775(223)	902(245)
		SF	50	54	66(21)	114(34)
		LB	46	65	71(30)	107(45)
		EX	19	84	729(658)	886(780)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	100	3.0(1.0)	3.0(1.0)
DIATOMACEA						
		PS	48	100	13866(3270)	13866(3270)
		SF	50	100	11683(4384)	11683(4384)
		LB	46	100	1170(241)	1170(241)
		EX	19	100	5346(2184)	5346(2184)
		OR	2	100	9409(6120)	9409(6120)
		HI	4	100	277(107)	277(107)
PROTOZOA						
		PS	48	83	316(122)	361(139)
		SF	50	90	5506(3638)	6120(4037)
		LB	46	93	210(57)	220(59)
		EX	19	74	82(58)	110(78)
		OR	2	100	31(13)	31(13)
		HI	4	100	4.0(1.3)	4.0(1.3)
CNIDARIA						
		PS	48	63	19.5(11.9)	55(32)
		SF	50	22	1.8(0.7)	8.3(2.3)
		LB	46	87	45(18)	53(21)
		EX	19	5	0.3(0.3)	5.7(0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
CTENOPHORA						
		PS	48	17	0.2(0.1)	1.2(0.3)
		SF	50	4	0.01(0.008)	0.5(0.0)
		LB	46	37	1.6(0.6)	4.0(1.5)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)

Table 3.1 continued

Phylum	Taxa	source	n	Prevalence (%)	mean(se) all ships	mean(se) when present
PLATYHELMINTHES						
		PS	48	27	3.4(1.4)	13(4.3)
		SF	50	28	10.5(4.6)	37(14)
		LB	46	80	11(2.2)	13(2.4)
		EX	19	16	0.1(0.07)	0.9(0.1)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
NEMATODA						
		PS	48	6	0.2(0.1)	2.5(0.9)
		SF	50	8	0.5(0.3)	6.5(2.4)
		LB	46	4	0.1(0.07)	2.5(0.5)
		EX	19	5	0.1(0.1)	1.4(0.0)
		OR	2	100	4.4(3.0)	4.4(3.0)
		HI	4	0	0(0.0)	0(0.0)
ROTIFERA						
		PS	48	2	0.3(0.3)	12.5(0)
		SF	50	2	0.7(0.7)	33(4.5)
		LB	46	2	0.6(0.6)	27(0.0)
		EX	19	5	0.3(0.3)	5.6(0.0)
		OR	2	50	0.2(0.2)	0.4(0.0)
		HI	4	0	0(0.0)	0(0.0)
SIPUNCULA						
		PS	48	0	0(0.0)	0(0.0)
		SF	50	4	0.8(0.7)	19.8(11)
		LB	46	4	0.7(0.6)	15(4.1)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
NEMERTEA						
		PS	48	8	1.0(0.6)	12.4(5.3)
		SF	50	8	41(27)	516(275)
		LB	46	15	23(12)	150(66)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
ANNELIDA		PS	48	90	370(136)	404(148)
		SF	50	80	199(55)	251(68)
		LB	46	100	33(6.5)	33(6.5)
		EX	19	2	2.1(1.3)	6.3(3.6
		OR	2	0	0(0.0)	0(0.0)
		HI	4	25	0.31(0.31)	1.2(0.0)
MOLLUSCA						
Bivalvia		PS	48	90	371(100)	396(106)
		SF	50	82	319(79)	389(93)
		LB	46	98	240(72)	246(74)
		EX	19	53	8.0(3.5)	15.2(5.5)
		OR	2	50	0.5(0.5)	1.0(0.0)
		HI	4	75	1.3(0.7)	2.0(0.5)

Table 3.1 continued

Phylum	Taxa	source	n	Prevalence (%)	mean(se) all ships	mean(se) when present
	Gastropoda	PS	48	71	139(39)	191(44)
		SF	50	54	34(18)	58(38)
		LB	46	91	35(7.6)	37(6.8)
		EX	19	37	26.6(17.6)	72(38)
		OR	2	50	0.2(0.2)	0.4(0.0)
		HI	4	0	0(0.0)	0(0.0)
	Other Mollusca	PS	48	8	8.0(7.7)	105(83)
		SF	50	6	0.6(0.5)	10(7.6)
		LB	46	2	0.2(0.2)	9.0(0.0)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
ARTHROPODA/CRUSTACEA						
	Amphipoda	PS	48	29	1.9(1.3)	6.1(3.8)
		SF	50	30	0.61(0.16)	1.9(0.3)
		LB	46	48	0.7(0.2)	1.4(0.3)
		EX	19	19	0.07(0.05)	0.7(0.2)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
	Anomura	PS	48	29	0.91(0.64)	3.7(2.2)
		SF	50	24	0.2(0.08)	0.9(0.3)
		LB	46	63	3.8(1.4)	5.9(2.1)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
	Brachyura	PS	48	44	3.5(1.3)	9.2(2.8)
		SF	50	14	0.13(0.07)	1.1(0.5)
		LB	46	76	23.6(13.9)	30.2(18.6)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
	Caridea	PS	48	15	0.2(0.10)	1.3(1.2)
		SF	50	2	0.02(0.01)	0.2(0.0)
		LB	46	22	1.2(0.60)	3.8(1.5)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)

Table 3.1 continued

Phylum	Taxa	source	n	Prevalence (%)	mean(se) all ships	mean(se) when present
	Cirripedia	PS	48	85	832(559)	951(637)
		SF	50	66	96(34)	108(47)
		LB	46	63	18(5.4)	37(7.2)
		EX	19	16	0.8(0.5)	6.9(1.7)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	50	3.1(1.9)	4.8(4.3)
	Cladocera	PS	48	15	2.7(1.2)	21.7(5.1)
		SF	50	16	1.9(0.8)	11.7(3.7)
		LB	46	7	0.04(0.02)	0.6(0.1)
		EX	19	5	0.3(0.3)	5.7(0.0)
		OR	2	100	3.5(1.9)	3.5(1.9)
		HI	4	0	0(0.0)	0(0.0)
	Copepoda	PS	48	100	2395(664)	2395(664)
		SF	50	100	9416(2060)	9416(2060)
		LB	46	100	5116(685)	5116(685)
		EX	19	100	2345(645)	2345(645)
		OR	2	100	43(6.0)	43(6.0)
		HI	4	100	8.2(4.4)	8.2(4.4)
	Cumacea	PS	48	10	0.05(0.03)	0.6(0.2)
		SF	50	30	0.70(0.2)	2.1(0.5)
		LB	46	22	0.13(0.05)	0.6(0.2)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
	Decapoda (misc.)	PS	48	4	0.05(0.04)	1.3(0.7)
		SF	50	8	0.02(0.02)	0.5(0.2)
		LB	46	4	0.05(0.02)	2.5(0.0)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
	Isopoda	PS	48	25	0.70(0.40)	2.1(1.3)
		SF	50	18	0.34(0.26)	2.1(1.5)
		LB	46	9	0.06(0.03)	0.7(0.1)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
	Mysidacea	PS	48	2	0.007(0.007)	0.3(0)
		SF	50	54	2.48(0.6)	4.6(0.9)
		LB	46	78	3.52(0.8)	4.4(0.9)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	25	0.15(0.15)	0.6(0.1)

Table 3.1 continued

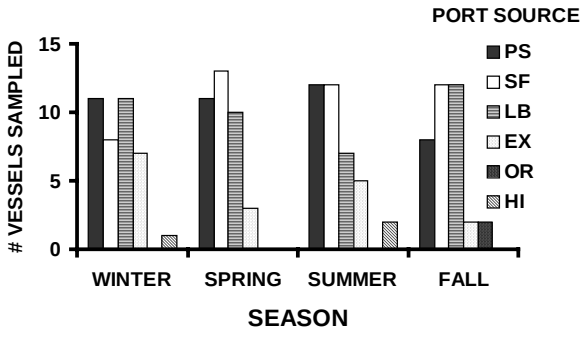
Phylum	Taxa	source	n	Prevalence (%)	mean(se) all ships	mean(se) when present
	Ostracoda	PS	48	25	0.35(0.16)	1.5(0.6)
		SF	50	8	0.40(0.20)	3.9(2.0)
		LB	46	17	0.28(0.14)	1.6(0.7)
		EX	19	16	0.93(0.54)	5.9(1.4)
		OR	2	50	0.6(0.6)	1.2(0.0)
		HI	4	0	0(0.0)	0(0.0)
	Tanaidacea	PS	48	2	0.006(0.006)	0.3(0)
		SF	50	0	0(0.0)	0(0.0)
		LB	46	2	0.006(0.006)	0.3(0)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
BRYOZOA						
		PS	48	35	16.1(5.4)	40.7(11.5)
		SF	50	40	59(33)	147(80)
		LB	46	22	1.5(0.5)	6.7(1.7)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
PHORONIDA						
		PS	48	2	0.01(0.01)	0.5(0.0)
		SF	50	2	0.01(0.01)	0.7(0.0)
		LB	46	15	0.5(0.4)	4.2(2.7)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
CHAETOGNATHA						
		PS	48	33	0.7(0.4)	2.3(1.1)
		SF	50	12	0.5(0.3)	4.1(2.5)
		LB	46	72	5.8(2.2)	7.9(3.0)
		EX	19	21	0.2(0.1)	1.5(0.3)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
ECHINODERMATA						
		PS	48	33	32(15)	94(43)
		SF	50	12	6.3(4.8)	53(37)
		LB	46	26	5.8(3.5)	22(12)
		EX	19	5	0.3(0.3)	6.0(0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
CHORDATA						
	Cephalochordata	PS	48	0	0(0.0)	0(0.0)
		SF	50	0	0(0.0)	0(0.0)
		LB	46	9	0.1(0.01)	2.8(2.5)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)

Table 3.1 continued

Phylum	Taxa	source	n	Prevalence (%)	mean(se) all ships	mean(se) when present
	Fish	PS	48	10	0.05(0.02)	0.3(0.1
		SF	50	6	0.02(0.01)	0.5(0.1
		LB	46	7	0.04(0.02)	0.5(0.1)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
	Other Chordata	PS	48	21	4.9(2.2)	23.8(8.4)
	(incl. larvacea)	SF	50	8	5.2(3.5)	85(41)
		LB	46	63	59.1(30.6)	107(55)
		EX	19	5	0.06(0.06)	1.2(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
OTHER						
	Eggs	PS	48	73	87(39)	113(50)
		SF	50	66	39(16)	56(22)
		LB	46	61	141(41)	232(148)
		EX	19	21	6.3(4.1)	15(9.2)
		OR	2	100	12(11)	12(11)
		HI	4	20	7.3(2.4)	7.3(2.4)
	Trochophore					
		PS	48	33	20(8.2)	65(23)
		SF	50	16	16(10)	115(65)
		LB	46	30	11(4.6)	36(13)
		EX	19	0	0(0.0)	0(0.0)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)
	Unidentified larvae	PS	48	0	0(0.0)	0(0.0)
		SF	50	4	95(93)	2376(1388)
		LB	46	9	0.02(0.02)	0.4(0)
		EX	19	11	27(26)	253(178)
		OR	2	0	0(0.0)	0(0.0)
		HI	4	0	0(0.0)	0(0.0)

For June of 1997-1999, we sampled the ballast water of 31 tankers arriving to Port Valdez from the domestic ports of Puget Sound (n=14), San Francisco Bay (n=9), and Long Beach (n=9). The data for 1998 and 1999 are included in the total 169 vessels sampled during this study, and the data for 1997 are derived from our previous work (as above).

Figure 3.1. Number of oil tankers sampled upon arrival to Port Valdez. Shown are the number of ships from which ballast water samples were collected by source port (i.e., last port of call) and season. Source ports include: Puget Sound, WA (PS); San Francisco Bay, CA (SF); Long Beach, CA (LB); Foreign port with open-ocean exchange (EX); Columbia River, Oregon (OR); and Barbers Point, Hawaii (HI). Seasons include: Winter (January-March), Spring (April-June), Summer (July-September), and Fall (October-December). Data were collected primarily from December 1997 – December 1998, and some additional data were collected in May-June 1999.

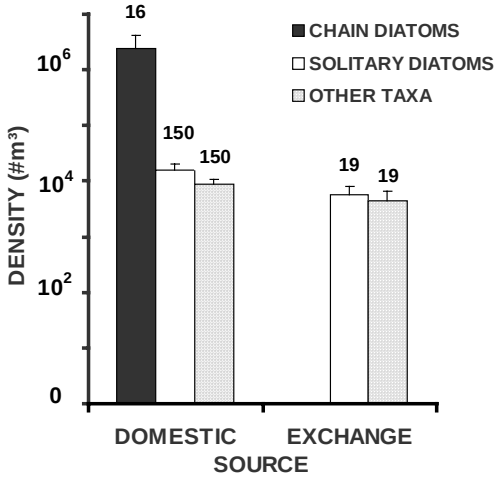


3C2. Abundance of Organisms in Ballast Water

(a) Total Density by Source

We measured an average of 12,637 (s.e. = 5,533) total organisms per m^3 in the ballast water for all 169 vessels from domestic and foreign source ports. This estimate excludes the chain-forming diatoms, which were detected in the samples from 16 domestic tankers. Although the chain-forming diatoms are difficult to quantify (as above), we estimated average densities in excess of one million organisms/m^3, approximately 100 fold higher than the densities of solitary diatoms and all other taxa measured for either domestic or foreign tankers (Fig. 3.2). We have excluded the chain-forming diatoms from the subsequent analyses and discussion of total density or abundance (i.e., abundance of all organisms) below.

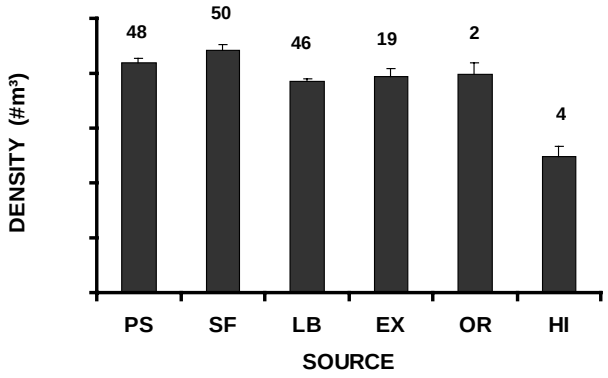
Figure 3.2. Densities of organisms in ballast water arriving to Port Valdez from foreign and domestic source ports. The estimated mean densities (#/m³ and standard errors) are shown separately for chain-forming diatoms, solitary diatoms, and all other taxa in ballast water of ships arriving from each domestic ports and foreign ports. Chain-forming diatoms were only detected on domestic ships (n=16), whereas the other groups were present on all domestic (n=150) and foreign (n=19) arrivals that were sampled. The data include all sample dates. Since arrivals from foreign ports all underwent ballast water exchange in open ocean, the source is indicated as exchange.



The average total density was significantly greater in ballast water from domestic sources compared to that for foreign sources (Fig. 3.2; 1-way ANOVA, $F_{(1,168)} = 3.63$, $P = 0.048$). The chain-forming diatoms were only evident in the ballast water of domestic arrivals, increasing the magnitude of density differences between foreign and domestic traffic.

The total abundance of organisms in ballast water differed among domestic sources. Of the three major domestic ports, arrivals from Puget Sound and San Francisco Bay had significantly greater densities than those from Long Beach and foreign sources, whereas the latter two were not different (Fig. 3.3; ANOVA, $F_{(2,143)} = 3.71$, $P = 0.027$). We excluded both Oregon and Hawaii from this comparison, due to the limited sample size and absence of data for some seasons. Although average density from Oregon arrivals was similar to that for Long Beach and foreign arrivals, density for Hawaii arrivals was over 10-fold lower than all others.

Figure 3.3. Densities of organisms in ballast water arriving to Port Valdez for each source port. The estimated mean densities (#/m³ and standard errors) are shown for all organisms by source port. The data include all sample dates (sample size indicated above bars) but exclude chain-forming diatoms. Source ports include: Puget Sound, WA (PS); San Francisco Bay, CA (SF); Long Beach, CA (LB); Foreign port with open-ocean exchange (EX); Columbia River, Oregon (OR); and Barbers Point, Hawaii (HI).



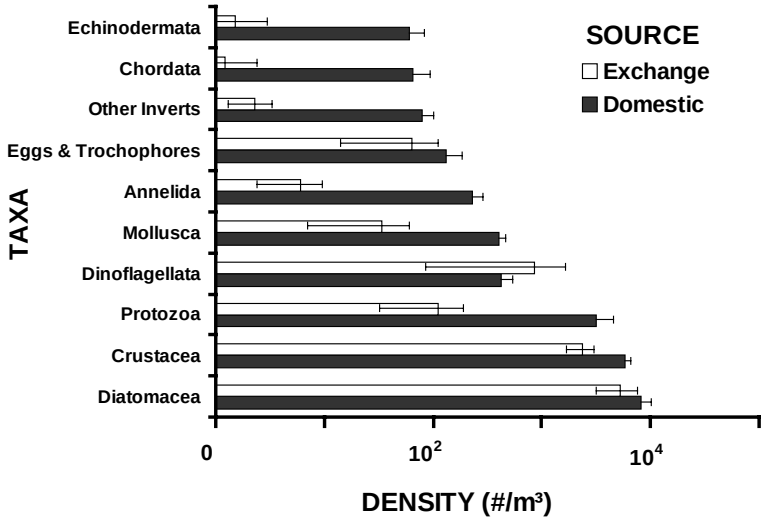
The average total densities among domestic source ports corresponded to voyage duration, with densities decreasing with voyage duration (see Fig. 2.7 of Chapt 2). Arrivals from Puget Sound and San Francisco Bay had the shortest voyage duration (average of 4.3 and 6.0 days, respectively) and highest densities. Tankers arriving from Hawaii had the longest voyage duration (average of 10.2 days) and lowest densities, whereas arrivals from Oregon and Long Beach were intermediate to the other domestic ports in both respects.

(b) Density by Taxonomic Group and Source

All ballast water samples contained living organisms, but the prevalence and density varied among taxonomic groups (Table 3.1). Copepods and diatoms were detected in ballast water from 100% of the ships sampled, and protozoans (primarily tintinnids) were found in nearly all samples. These three groups also exhibited the highest densities, dominating the plankton community in ballast water (see below).

As with the total density measures, most taxonomic groups also occurred at greater average densities in ballast water from domestic sources, when pooled, compared to that from foreign sources (Table 3.1 and Fig 3.4). For most groups, this difference was 10- to 100-fold. The magnitude of density differences between domestic and foreign sources were much less for crustaceans, primarily due to the presence of copepods (see Table 3.1) and solitary diatoms. Dinoflagellates were a notable exception to the general pattern, as average density was greatest in ballast water of the foreign arrivals.

Figure 3.4. Densities of major taxonomic groups in ballast water arriving to Port Valdez from foreign and domestic source ports. The estimated mean densities (#/m³ and standard errors) are shown separately for 10 different major groups of organisms in ballast water of ships arriving from each domestic ports (n=150) and foreign ports (n=19). Eight groups are distinct phyla that were most abundant in the ballast water, and two are composed of multiple phyla, including eggs and trochophores (which were abundant but could not be classified by phylum) and all other invertebrates. The data include all sample dates. Since arrivals from foreign ports all underwent ballast water exchange in open ocean, the source is indicated as exchange.



On a finer scale, significant variation existed in the abundance of taxonomic groups among specific source port systems (Fig. 3.5 and Table 3.1). More specifically, differences were present when comparing mean densities for each taxonomic group among Puget Sound, San Francisco Bay, Long Beach, and foreign arrivals (ANOVA, see Fig. 3.5 for statistically significant differences). Among these four ports, the densities of most taxa were relatively low for foreign arrivals, with the exception of diatoms and dinoflagellates. This pattern resulted from both the prevalence and densities of taxa among vessels. For example, the prevalence of most taxa was low in the ballast water of foreign arrivals, although the densities may not been particularly low for the few ships where a taxon was detected (Table 3.1). Across all arrivals, mean densities of the various taxa were generally lowest for both Oregon and Hawaii, although the limited sample size precludes any formal analysis.

In contrast to total organism density, the greatest average densities for taxonomic groups did not always correspond to the shortest voyage duration (Fig. 3.5 and Table 3.1). For example, the highest average densities of protozoans, crustaceans, and bryozoans were measured for San Francisco Bay arrivals, and the brachyuran crabs were most abundant in samples from Long Beach.

(c) Seasonal Variation in Density

Significant differences among months were present in the total densities of organisms present in domestic ballast water (Fig. 3.6; ANOVA, $F_{(11,168)} = 1.98$, $P = 0.033$). This resulted primarily from a relative increase during the spring and summer months.

Figure 3.5. Densites of major taxonomic groups in ballast water arriving to Port Valdez for each source port. The estimated mean densities (#/m³ and standard errors) are shown separately for 10 different major groups of organisms in ballast water of ships by source port. Eight groups are distinct phyla that were most abundant in the ballast water, and two are composed of multiple phyla, including eggs and trochophores (which were abundant but could not be classified by phylum) and all other invertebrates. Source ports include: Puget Sound, WA (PS); San Francisco Bay, CA (SF); Long Beach, CA (LB); Foreign port with open-ocean exchange (EX); Columbia River, Oregon (OR); and Barbers Point, Hawaii (HI). The data include all sample dates. Sample sizes for each source port as shown in Figure 3.3. Indicated by * are those taxa where mean density among ports, excluding HI and OR, is significantly different by ANOVA with confidence ≥95%.

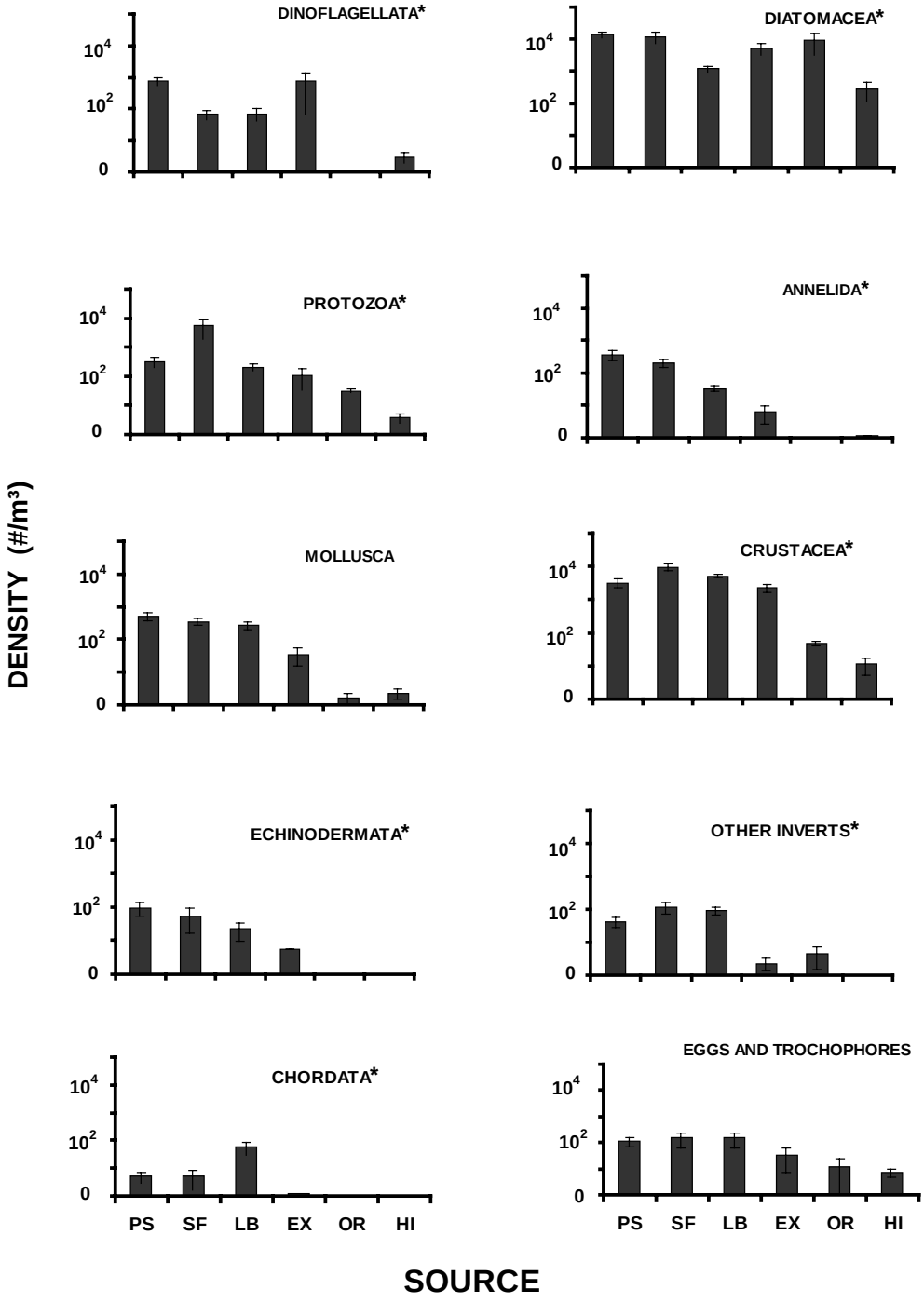
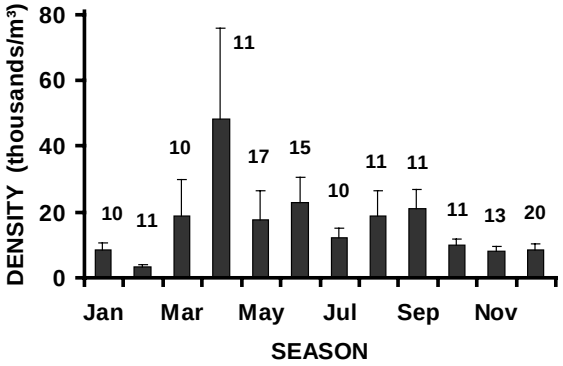
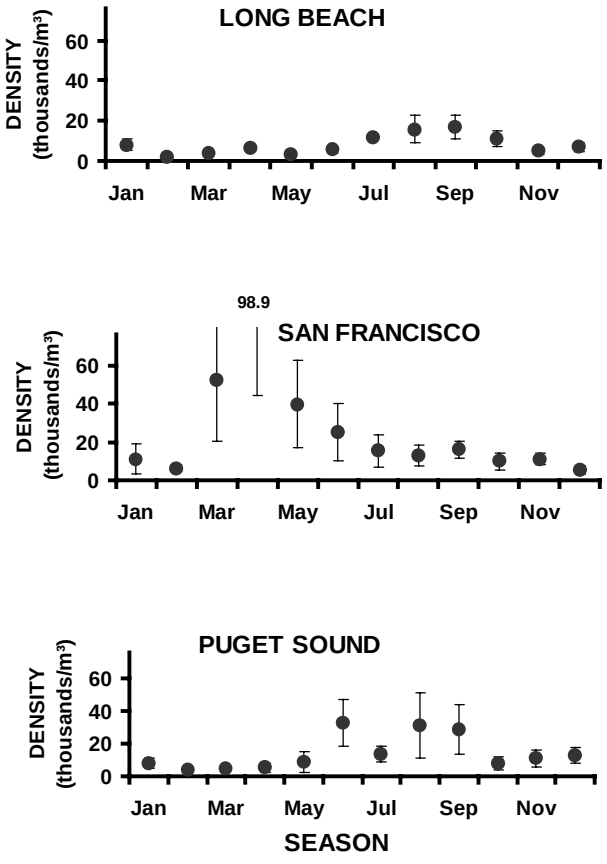


Figure 3.6. Monthly densities of organisms in ballast water arriving to Port Valdez from domestic source ports. The estimated mean densities (#/m³ and standard errors) are shown for all organisms, except chain-forming diatoms, by month. The data for all domestic source ports are included in each month (sample size shown above bars).



The seasonal pattern in total density varied among arrivals from the 3 major domestic ports (Fig. 3.7). Arrivals from San Francisco Bay exhibited a strong spring peak in total plankton density, whereas the peak appeared later in arrivals from Puget Sound. In contrast, the density of organisms arriving from Long Beach was relatively stable throughout the year.

Figure 3.7. Monthly densities of organisms in ballast water arriving to Port Valdez by domestic source ports. For each of the three major domestic source ports, the estimated mean densities (#/m³ and standard errors) are shown for all organisms, except chain-forming diatoms, by month. Sample size for each source port as follows, from left to right: Long Beach – 3,4,4,4,5,4,2,2,3,4,6,5; San Francisco –2,3,3,5,6,5,2,4,4,4,5,7; Puget Sound – 5,3,3,2,5,6,5,4,4,3,2,6.



For the individual taxonomic groups, densities varied both by source port and month (Fig. 3.8). In general, peak densities occurred between spring and summer months for all taxonomic groups, but the timing of these peaks differed among groups. Summed across the three major domestic ports (Puget Sound, San Francisco Bay, and Long Beach; Fig. 3.8a):

- Dinoflagellates, echinoderm larvae, chordates, and the combined eggs and trochophores exhibited peak mean densities in late summer;
- Protozoans and diatoms exhibited a spring to early summer peak in mean density.
- Molluscs and crustaceans for these combined ports were relatively high from spring through summer, exhibiting a bimodal distribution with spring and later summer peaks;
- Annelids exhibited peaks in density during the summer months of June and August;
- All other invertebrates, when combined, had relatively high densities from early spring through fall compared to the remainder of the year.

The relative contributions of the three port systems to the overall temporal patterns varied significantly (Fig 3.8b-d). The general seasonal patterns (i.e., spring-summer peaks) in density were similar among ports, but clear differences existed in the magnitude and month of peak densities among ports. As noted previously for total density across the entire year (Fig. 3.5), the magnitude of peaks for the taxonomic groups did not correspond consistently to voyage duration.

(d) Annual Variation in Density

There were significant differences among years in the total density of plankton arriving from the three major ports for June 1997-1999 (Fig. 3.9). A 2-way ANOVA revealed differences among years ($F_{(2,32)} = 3.28$, $P = 0.055$) but not ports ($P>0.05$), and the interaction was not significant ($P>0.05$).

The magnitude of variation among years was more pronounced for the individual taxonomic groups in each of these ports (Fig. 3.10). Over half of the taxonomic groups exhibited significant differences among years, when analyzed individually for each port source (1-way ANOVA, see Fig 3.10 for statistically significant differences). As discussed above, some groups (e.g., echinoderm larvae and chordates) could not be compared statistically, due to low prevalence among ships.

Interestingly, the changes among years were not consistent among port sources. For example, dinoflagellates increased in successive years for Puget Sound and Long Beach arrivals, but was greatest in 1998 and virtually absent in the other two years for San Francisco arrivals. While peak years in protozoan and crustacean densities were similar among the port sources, the peak years for all other taxa were highly divergent among the port sources.

Figure 3.8. Monthly densities of major taxonomic groups in ballast water arriving to Port Valdez from domestic source ports. The estimated monthly mean densities (#/m³ and standard errors) are shown separately for 10 different major groups of organisms in ballast water of ships arriving from domestic ports. Eight groups are distinct phyla that were most abundant in the ballast water, and two are composed of multiple phyla, including eggs and trochophores (which were abundant but could not be classified by phylum) and all other invertebrates. For each taxonomic group, the monthly mean densities are shown for: (a) Puget Sound; (b) San Francisco; (c) Long Beach; and (d) the three major ports combined. Sample size for each port as indicated in Figure 3.7.

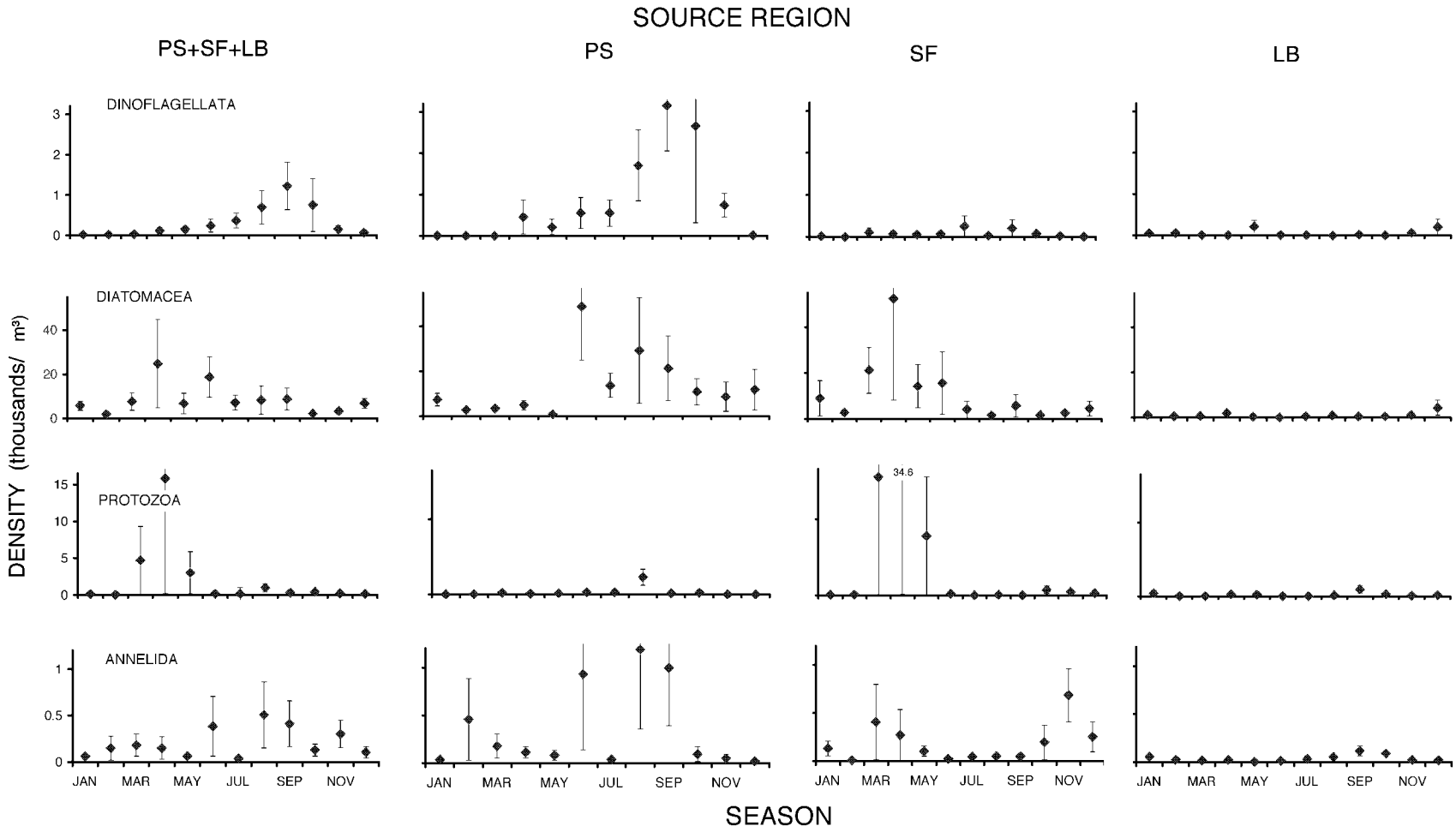


Figure 3.8 continued.

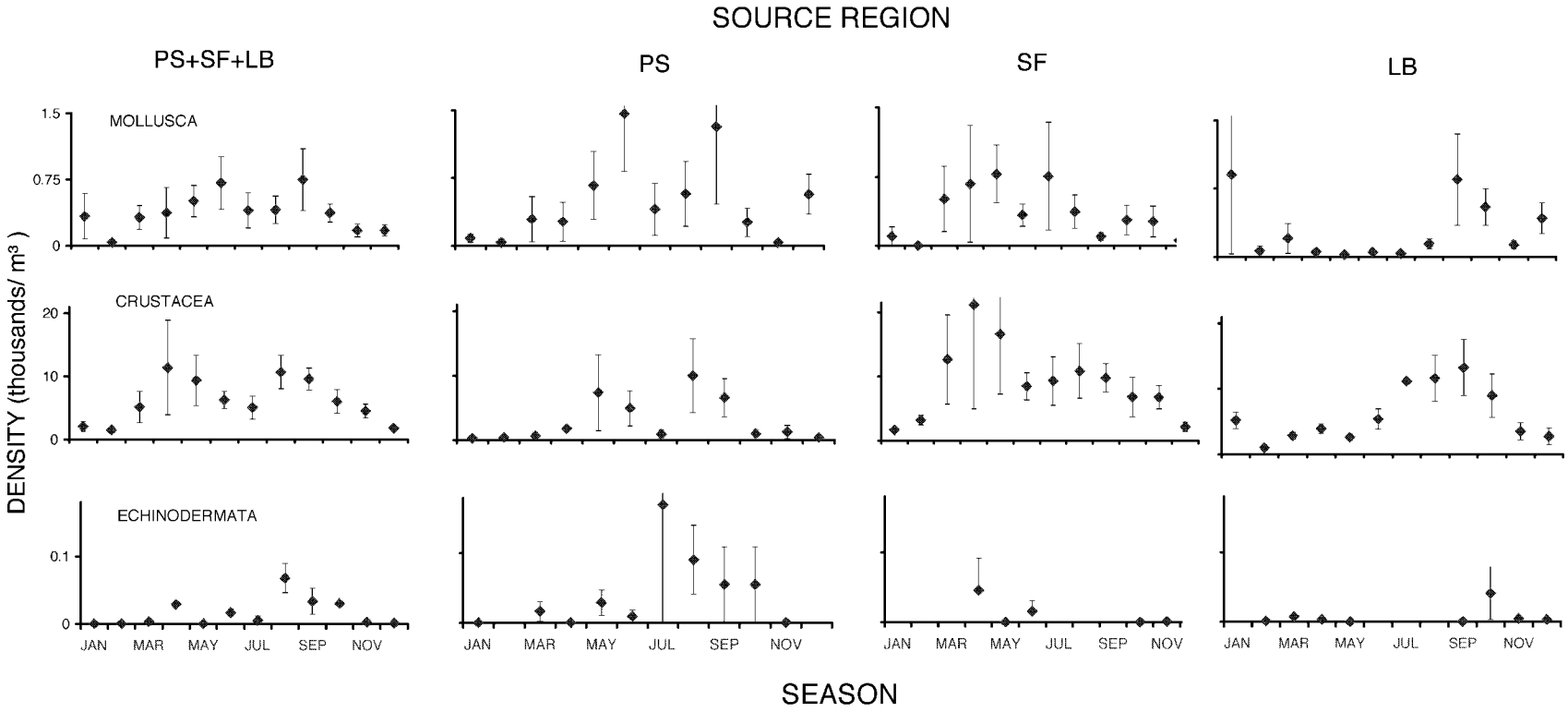


Figure 3.8 continued.

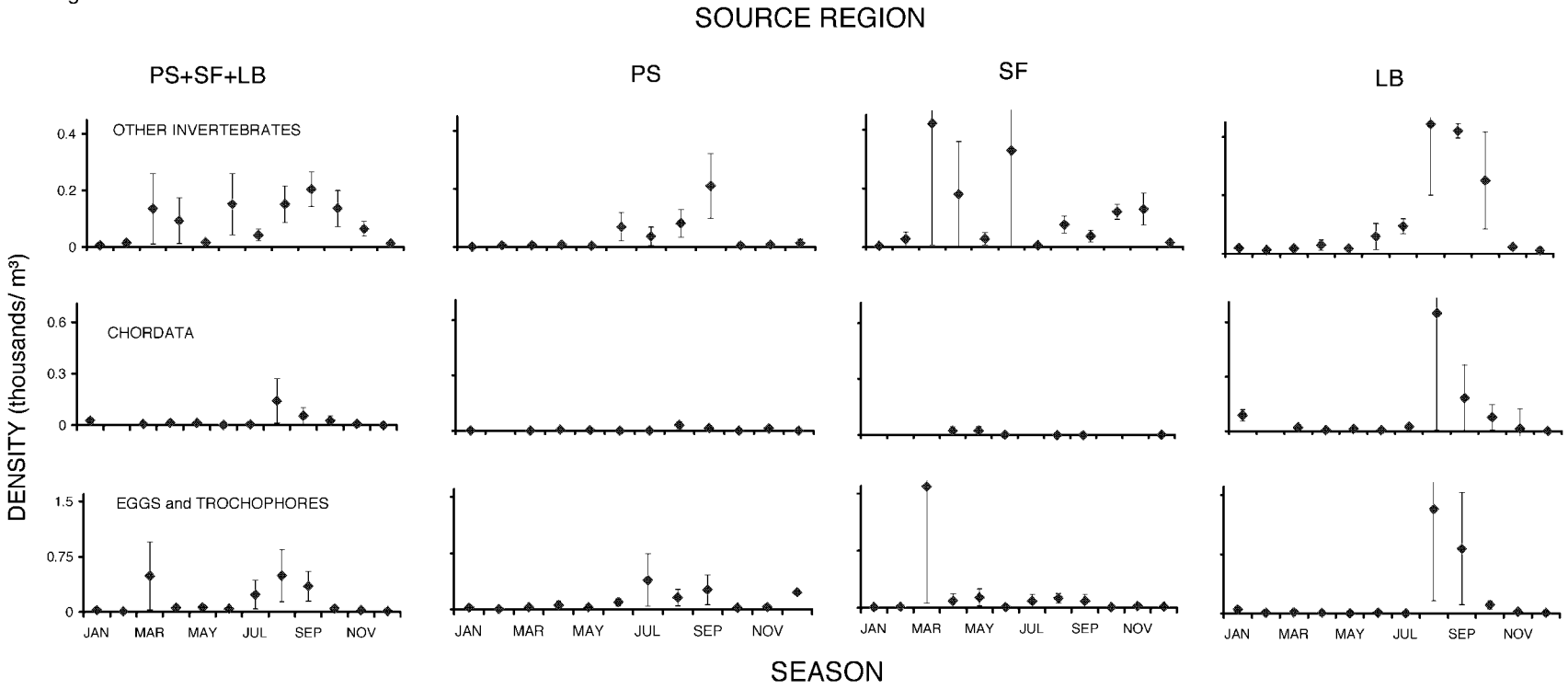


Figure 3.9. Densities of organisms in the ballast water arriving to Port Valdez from domestic ports in June of three consecutive years, 1997-1999. The estimated mean densities (#/m³ and standard errors) are shown for all organisms, excluding chain-forming diatoms, by source port in each year (sample size indicated above bars). Source ports include: Puget Sound, WA (PS); San Francisco Bay, CA (SF); Long Beach, CA (LB). Densities are also shown by year for all three source ports combined (Overall).

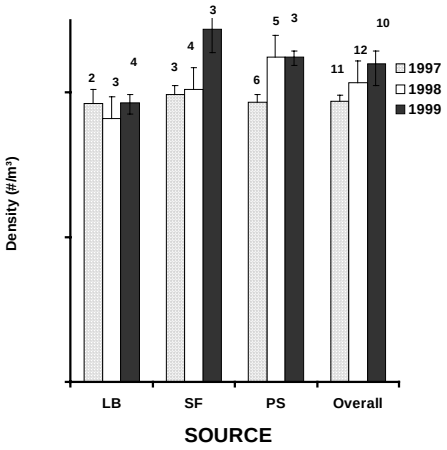
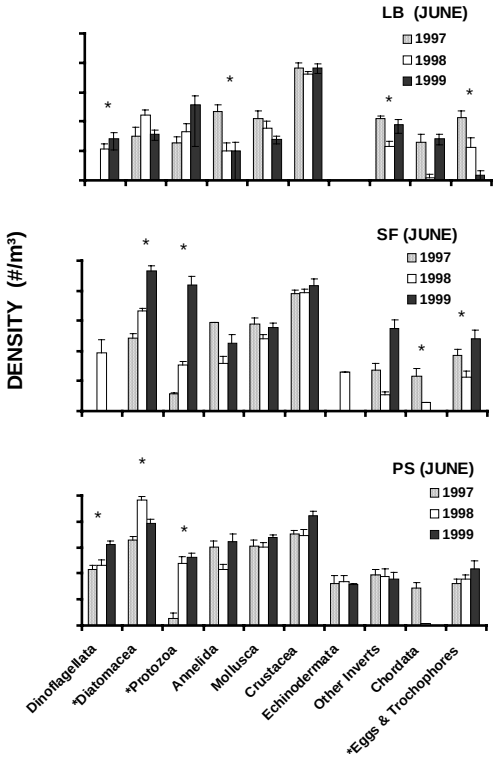


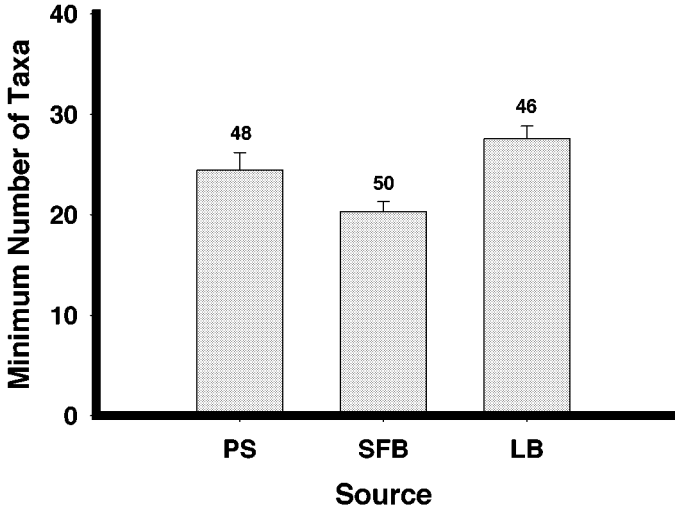
Figure 3.10. Densities of major taxonomic groups in the ballast water arriving to Port Valdez from domestic source ports in June of three consecutive years, 1997-1999. The estimated mean densities (#/m³ and standard errors) are shown for 10 different major groups of organisms in ballast water of ships arriving by year from three different source ports. Eight groups are distinct phyla that were most abundant in the ballast water, and two are composed of multiple phyla, including eggs and trochophores (which were abundant but could not be classified by phylum) and all other invertebrates. Sample size for each source port and year as indicated in Figure 3.9. Indicated by * are instances where ANOVA showed significant differences in density among years (above bars) and among ports (below taxa labels) with confidence ≥95%.



3C3. Diversity of Organisms in Ballast Water

In a preliminary analysis of our Fine Analysis data (see Methods), there was a significant difference in the minimum number of taxa, and/or species richness, detected among arrivals from the three main domestic ports (Fig. 3.11). The average species richness was greatest for Long Beach arrivals and lowest for San Francisco Bay arrivals, and it does not correspond to voyage duration.

Figure 3.11. Minimum number of taxa detected in the ballast water arriving to Port Valdez by domestic source ports. Shown are the mean number (including standard errors and sample size, above bars) of distinctly different taxa observed in plankton samples of ships from each source port. Source ports include: Puget Sound, WA (PS); San Francisco Bay, CA (SF); Long Beach, CA (LB). All sample dates included.



The season of peak species richness differed among port sources (Fig. 3.12). Arrivals from Puget Sound and San Francisco Bay exhibited peaks in mean species richness in the spring and summer, whereas those from Long Beach had their highest species richness in the fall and spring. Subsequent analyses indicated differences among source ports for each season, as well as differences among seasons for each source port (1-way ANOVA, Fig. 3.12 indicates statistically significant differences).

To date, we have identified 14 different nonindigenous species arriving to Port Valdez in the ballast water of oil tankers (Table 3.2). One is a fish species and all the other species are crustaceans (copepods and amphipods, which have successfully invaded the respective source ports of arriving tankers. To date, all of these identified NIS have been in ballast water from San Francisco and Long Beach.

We expect the cumulative list will increase, as final identifications are still underway for the Fine Analysis data. Upon completion, we will report the frequency and density of these NIS in ballast water arriving from the respective source ports.

Figure 3.12. Minimum number of taxa detected in the ballast water arriving to Port Valdez among domestic source ports and seasons. Shown are the mean number (including standard error above bars) of distinctly different taxa observed in plankton samples of ships from each source port and season. Source ports include: Puget Sound, WA (PS); San Francisco Bay, CA (SF); Long Beach, CA (LB). Seasons include: Winter, (December – February); Spring (March – May); Summer (June – August); and Fall (September – November). Indicated by * are significant differences (ANOVA with confidence ≥95%) in diversity among seasons within port (see legend) and among ports within season (see x-axis labels).

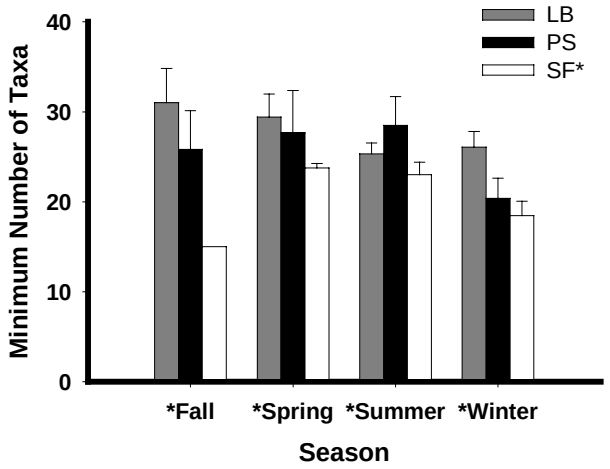


Table 3.2. Nonindigenous species identified in ballast water arriving to Port Valdez. The source of ballast water is indicated in which each species was detected; when two sources are indicated, the species was found in ballast water from each source port. Source ports are: San Francisco Bay, CA (SF); Long Beach, CA (LB).

Broad Taxa	Species	Ballast Source
Amphipoda	*Ampelisca abdita*	SF and LB
	Monocorophium acherusicum	SF
	Sinocorophium heteroceratum	LB
	Gammarus daiberi	SF and LB
	Grandidierella japonica	SF
Copepoda	*Limnoithona tetraspina*	SF
	Oithona davisae	LB
	Acartiella sinensis	SF
	Pseudodiaptimus marinus	SF
	Pseudodiaptimus forbesi	SF
	Sinocalanus doerrii	SF
	Tortanus dextrilobatus	SF
Mysidacea	*Acanthomysis bowmani*	SF
Chordata	*Acanthogobius flavimanus*	SF

3D. Discussion

Our analysis indicates that significantly greater numbers of organisms are discharged into Port Valdez and PWS in oil tankers arriving from domestic ports compared to those from foreign ports. This results from the number of arrivals and the density of organisms in their ballast water, as both are greatest for the domestic arrivals. Accounting for number of arrivals and density (by source port and season), Table 3.3 estimates the total supply of plankton that we

sampled to be roughly 264 billion organisms in 1998. Of this, approximately 3% arrived from foreign traffic.

The differences observed in total density, as well as taxon-specific density, among arrivals from different source ports may result from a combination of multiple factors, including (a) differences in initial densities, (b) differences in survivorship, and (c) effects of ballast water exchange (conducted for foreign but not domestic arrivals).

Table 3.3. Estimated number of large, planktonic organisms delivered in tankers' ballast water to PWS and Port Valdez in 1998. Shown by source port and season are (1) the estimated total ballast water volumes, (2) mean densities of planktonic organisms, including standard errors and sample size, and (3) total number of planktonic organisms arriving in the ballast water of oil tankers. Total Volumes are derived from Table 2.1. Mean densities were estimated from analysis of plankton samples, which were collected by 80micron net, and exclude chain-forming diatoms (see text for description). Where no samples were available for a season (e.g., Hawaii and Oregon), the grand mean across all samples of that source port was used. The bottom row (Overall) estimates the total ballast water volumes and total organisms delivered as a sum. Source ports include: Puget Sound, WA (PS); San Francisco Bay, CA (SF); Long Beach, CA (LB); Foreign port with open-ocean exchange (EX); Columbia River, Oregon (OR); and Barbers Point, Hawaii (HI). Seasons include: Winter (January-March), Spring (April-June), Summer (July-September), and Fall (October-November).

			Density organisms (#/m³)				
			Phyto.+Zoopl.	Zoopl.		Phyto.+Zoopl. Delivered	Zoopl. Delivered
Port/Source	Season	Total BW (m³)	Mean(se)	Mean(se)	n	Billions	Billions
	Winter	1,802,432	5963(1432)	879(343)	11	10.75	1.58
	Spring	1,885,260	17602(9543)	3427(1423)	11	33.18	6.46
PS	Summer	2,032,432	24116(8198)	8539(3062)	12	49.01	17.35
	Fall	1,796,382	8546(2636)	1269(384)	8	15.35	2.28
	Grand total	7,516,506			42	108.30	27.68
	Winter	1,082,594	24686(13263)	13435(9497)	8	26.72	14.54
	Spring	1,345,169	48504(23134)	29876(14848)	13	65.25	40.19
SF	Summer	1,573,660	14572(2914)	10696(1959)	10	22.93	16.83
	Fall	1,340,469	8840(1961)	7162(1488)	12	11.85	9.60
	Grand total	5,341,892			43	126.75	81.17
	Winter	585,468	4298(1094)	3426(954)	11	2.52	2.01
	Spring	395,187	4848(667)	3734(490)	10	1.92	1.48
LB	Summer	504,630	15951(3274)	15145(3175)	6	8.05	7.64
	Fall	390,180	6574(1613)	5508(1639)	12	2.57	2.15
	Grand total	1,875,465			39	15.05	13.27
	Winter	379,377	8791(3127)	1852(423)	7	3.34	0.70
	Spring	265,764	3466(2144)	1634(775)	3	0.92	0.43
EX	Summer	149,280	18447(14784)	3393(3141)	5	2.75	0.51
	Fall	141,168	3571(1398)	3179(1100)	2	0.50	0.45
	Grand total	935,589			17	7.51	2.09
	Winter	262,638	-	-	0	2.49	0.02
	Spring	113,000	-	-	0	1.07	0.01
OR	Summer	97,287	-	-	0	0.92	0.01
	Fall	273,966	9474(6138)	65(13)	2	2.60	0.02
	Grand total	746,891				7.08	0.05
	Winter	189,994	772	17	1	0.15	0.00
	Spring	111,145	-	-	0	0.05	0.00
HI	Summer	142,596	102(72)	14(2)	2	0.01	0.00
	Fall	108,370	-	-	0	0.05	0.00
	Grand Total	552,105			3	0.26	0.01
Overall		16,968,448			145	264.94	124.26

Among the domestic arrivals, many of the observed differences in prevalence and density probably result from initial differences at the locations where ballast tanks are filled. For example, this may explain the especially strong differences observed in densities of some organisms, such as dinoflagellates and protozoans (Fig. 3.8), among source ports. Although we have very limited data on the initial densities within ballast tanks at the start of the tankers' voyages (see Chapter 5), the published literature indicates that significant variation in the density and diversity of plankton communities among these and other source ports should be expected. In this context, it is perhaps important to recognize some conspicuous differences that existed among the domestic source ports. Certainly there are many differences in the habitat characteristics (e.g., composition, extent, quality, proximity to ports, etc), which may influence what is initially entrained in the tankers' ballast tanks. However, there are also two physical/chemical characteristics that are widely recognized to influence the composition and dynamics of biotic communities: temperature and salinity. Temperature clearly differed among domestic port systems, increasing from north to south. Among the major domestic ports, salinity was extremely low for San Francisco Bay compared to Puget Sound and Long Beach in 1998, in which rainfall was relatively high (due to El Nino Southern Oscillation) and had a disproportionately large effect on salinity in San Francisco Bay.

Despite any initial differences in plankton communities, it is evident that survivorship during transit can contribute strongly to the observed differences in biota arriving from various source ports. A variety of studies have now shown a significant decline in the density of planktonic organisms in ballast tanks during voyages, and the magnitude of decline is time-dependent, increasing significantly with voyage duration (Wonham et al. 1996, LaVoie et al 1999, Smith et al. 1999; however see below for possible exceptions). We have obtained similar results aboard oil tankers arriving to Port Valdez (Chapter 5). For most taxa, the decline has been attributed to mortality. However, for a few groups included in our analysis, such as diatoms and dinoflagellates, it is possible for the organisms to develop dormant stages that can accumulate on the bottom of ballast tanks.

Ballast water exchange undoubtedly had a significant effect on the plankton community associated with foreign arrivals, contributing to the major differences in biota between foreign and domestic arrivals. Exchange can significantly reduce the concentration of many organisms within ballast tanks, and it can also entrain additional organisms from the oceanic site of exchange (Ruiz et al. 1997, 1999; see also Chapter 5). In our study, the combination of ballast water exchange and voyage duration (which was relatively high for foreign ports) would both operate reduce initial densities of coastal plankton and contribute to the lower abundance of many taxonomic groups in ballast water of foreign arrivals compared to that from domestic arrivals. In contrast, the domestic arrivals did not undergo ballast water exchange and arrived to Port Valdez with the initial coastal water, following a relatively short voyage.

We hypothesize that the combined effects of ballast water exchange and voyage duration, instead of initial densities, were responsible for observed differences in abundance of coastal organisms between domestic and foreign arrivals. More specifically, we suggest that these forces reduced the densities of predominantly coastal organisms such as cnidarians, flatworms, annelids, molluscs, chordates, echinoderms, bryozoans, barnacles, and many other crustacean groups (see Chapter 5 for further discussion).

The effects of ballast water exchange for some taxonomic groups, and its contribution to observed differences in their abundance between foreign and domestic arrivals, is not so well resolved. Unlike the low abundance of coastal organisms, foreign arrivals had relatively high densities of dinoflagellates, copepods, and solitary diatoms in their ballast water. Most of these organisms were probably oceanic in origin and were entrained during the exchange process. This is certainly the case for the copepods, for which the species were recognized as oceanic and the generation time is in excess of the voyage duration. However, there is some suggestion that an increase of phytoplankton can result from ballast water exchange, as generation times are relatively short and the organisms may respond rapidly to changes in water quality following exchange (Gollasch et al.1998, LaVoie et al. 1999). The extent to which populations of these taxa, either of coastal or oceanic origin, may have increased following exchange is uncertain.

The temporal variation observed in plankton densities was largely expected. In general, the seasonal peaks in density corresponded to seasonal production and density variation measured for plankton in north temperate estuaries. The magnitude of variation observed among years also is evident in field studies, including especially an El Niño event such as that for 1998. The heavy rainfall in that year was associated with especially high densities of protozoans, solitary diatoms, and copepods in the arrivals from San Francisco Bay.

Although we have identified 14 nonindigenous species in the ballast water arriving to Port Valdez, and have provided some comparative data on species richness, these results must be viewed with caution. Clearly these numbers are minimum estimates. Although both estimates will increase upon completion of the voucher identification (see results), the measures can only be applied to a subset of the taxa and will always represent a minimum value. More specifically, most of the larval invertebrates (e.g., molluscs, barnacles) include many different species, which cannot be readily distinguished as larvae. All bivalve larvae are therefore treated as one species in our analysis, masking the diversity that most certainly exists. Thus, this approach is useful primarily in describing minimum diversity of native and exotic species arriving in ballast water, and does not necessarily reflect actual diversity patterns in space or time.

It is also important to recognize that our conclusions about patterns of abundance and diversity are focused on the large (>80 micron) segment of the plankton community within ballast tanks. We have provided some additional qualitative information about the macrofauna found on the bottom of tankers' ballast tanks (Chapt 6, this report). Thus, our data do not address density or diversity of microorganisms and taxa missed by an 80 micron mesh. The dynamics of these groups are very much in debate, as few good data exist to discern the potential for population changes (either declines or increases), due especially to mortality, dormancy and cyst formation, or ballast water exchange.

Beyond the variation in plankton delivery by time and source port, our data underscore that both the concentration and cumulative amount of plankton arriving in tankers' ballast water to Port Valdez and PWS is relatively high compared to that estimated for other ports (e.g., Carlton and Geller 1993, Smith et al. 1999). This results from both the volume of water delivered (Chapter 2) and the concentration of plankton, as both values are relatively high. We hypothesize that the abundant plankton results from the short voyage duration for domestic traffic, accounting for approximately 97% of the total tanker arrivals at present. In contrast,

although Chesapeake Bay receives more total ballast water per year than PWS, most of the ballast water comes from Europe, arriving in 10-14 days with an average concentration of 200 organisms / m^3 (Smith et. al. 1999; Ruiz et al., unpubl. data). Furthermore, it appears that ballast water arriving to the Chesapeake from domestic ports also has a lower density than that arriving to PWS from domestic ports.

Finally, from an invasion perspective, there are three unusual features of our analysis that deserve explicit mention:

- This is the most comprehensive analysis of domestic, coastwise ballast transfer. Most organisms that arrive in ballast water to PWS come from domestic source ports, which are themselves highly invaded. Thus, our study examines the opportunity for sequential invasions, which can "leapfrog" up the coast following initial colonization of North America.
- The delivery of ballast water by tankers to Port Valdez is a relatively recent development, beginning in 1977. Although many features may influence the risk of invasion, it is often considered to increase with the frequency, density, and duration of inoculation. Our results indicate that the risk associated with the first two of these is relatively high. However, the operation of this transfer mechanism has only existed for three decades. Even at the current rates of organism delivery (see above), invasion success may be influenced strongly by duration. In contrast, many other ports have been receiving ballast water and ballast materials for a century or more.
- Delivery of ballast water from foreign sources by tankers is even a more recent development, beginning in 1996. Although this accounted for only 3% of the total volume of ballast water delivered in 1998, all of the ballast water delivered by foreign arrivals had undergone exchange. Some coastal organisms remained in the exchanged tanks (see Chapter 5); however, the total supply of organisms from foreign ports is both relatively small and extremely recent compared to other port systems.

3E. References

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