Predicting effects of dredging on a crab population: An equivalent adult loss approach

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Abstract.–The effect of benthic dredging on coastal fisheries has been of concern for several decades, but little work quantifying direct population impacts has been published. Modeling approaches have been used extensively to assess effects of power plant entrainment on fishery stocks. Several important differences between power plant and dredge operations prevent direct application of these models to dredge problems: Entrainment by dredges is short-term, has a moving intake, and affects all age-classes of the population. We present an equivalent adult loss model of impacts to the Washington coast Dungeness crab *Cancer magister* Dana fishery from dredging of a navigation channel in Grays Harbor, Washington. The model is driven by empirical population data to account for spatial and temporal variation in abundance and age-class structure. Results show that impacts are quite sensitive to the type of dredge used and the season in which dredging occurs. Contrary to initial expectations, the 0+ age-group loss was unimportant relative to losses from older age-classes. Despite many limitations, the model has proven useful for focusing impact assessment work, as a basis for scheduling construction to reduce impacts, and as a basis for scaling mitigation projects.

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The effect of dredging on marine organisms has been an issue of environmental concern for several decades. Most studies on the impact of dredging and disposal of dredged material are concerned with changes in infaunal species assemblages and community characteristics, and generally measure effects by pre- and post-dredging comparisons. Very little work has been done on the direct effects of entrainment on populations of mobile epibenthic invertebrates or demersal fish, in part because such species are difficult to quantify. The reviews by Morton (1977) and Poiner and Kennedy (1984) indicate a strong research emphasis on habitat modification (by either dredging or disposal of sediments) and water column effects (turbidity, release of chemical pollutants) during dredging operations. Water column effects were also the focus of a workshop on anadromous fish and dredging (Simenstad 1990). Virtually no published works report on direct population losses due to entrainment or burial during dredging, except Stevens (1981) and Armstrong et al. (1982). There are few predictive models of dredging impacts other than that of Bella and Williamson (1980), who developed a model of dredging effects in Coos Bay, Oregon. Their model focused on water chemistry and sediments, but also gave some consideration to broad categories of animals.

In sharp contrast, power plant entrainment and impingement of fish has generated a large quantitative modeling literature (e.g. van Winkle 1977). Among the methods used in power plant assessments, the "equivalent adult loss" (Horst 1975, Goodyear 1977) and "production foregone" (Rago 1984) approaches are transferable to dredging operations, if sufficient biological and operational data are available. There are, however, several noteworthy differences between power plant and dredging operations which require different considerations in their analyses. Firstly, power plant water intakes operate continuously at a fixed location, while dredging operations are generally short-term, with a moving intake. This means that continuous, equilibrium approaches (e.g., MacCall et al. 1982) are not appropriate for dredging. Secondly, mobile benthic invertebrate populations are characterized by spatial aggregations and seasonal shifts in distribution which must be taken into account in estimating entrainment by a moving dredge. Finally, power plant entrainment is usually restricted to a single age-class (larvae or early juveniles), whereas dredging removes all age-classes present in the dredged habitat, but may kill age-classes at different rates.

The work we describe here applies an equivalent adult loss model (the "Dredge Impact Model" or "DIM") to assessing entrainment loss to the Dungeness crab *Cancer magister* Dana fishery in and around Grays Harbor, Washington. The Grays Harbor navigation channel (Fig. 1) extends from the harbor mouth to the city of Aberdeen, a distance of about 25 km. The U.S. Army Corps of Engineers currently removes an average of 1.2 million m^3 of sediment annually from the channel during maintenance dredging. To improve accessibility for deep draft vessels, the Corps planned to widen and deepen the channel by removing about 8.7 million m^3 of material over a two-year period (McGraw et al. 1988). Based on results and predictions of DIM, the Corps changed their original dredging program by modifying gear, volume dredged, and location/season combinations to minimize impact on crab within operational constraints (including weather and protection of other resources). Project construction took place throughout 1990, ending in January 1991. This paper extends an initial analysis (Armstrong et al. 1987), incorporating two additional years of biological data and providing a more thorough analysis of year-to-year variation. The study was undertaken in response to concerns of crab fishermen and resource managers that Grays Harbor is important as a juvenile crab nursery.

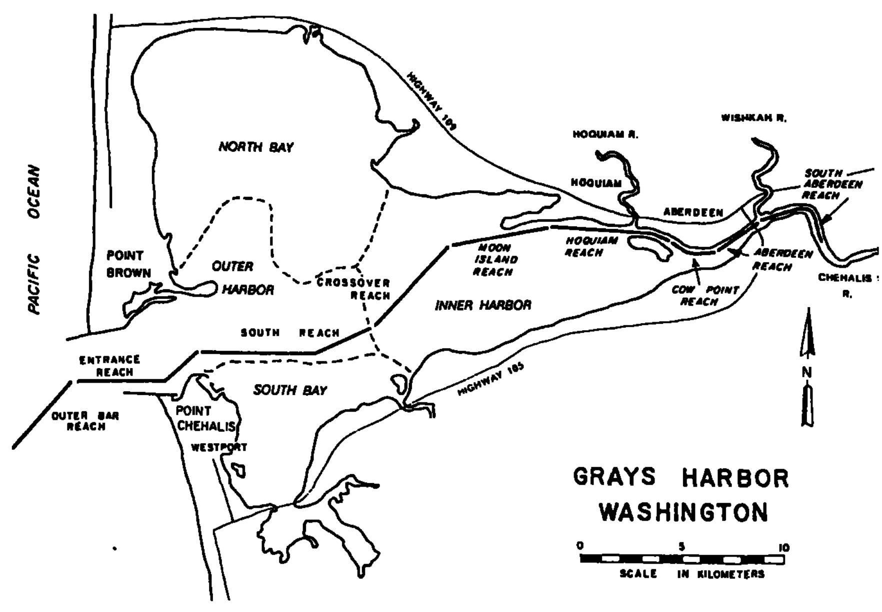

Figure 1
Map of Grays Harbor, Washington, showing existing navigation channel (heavy solid line) and sampling strata (separated by dashed lines).

Dungeness crab provide major fisheries along the west coast of North America, from central California to southern Alaska (Botsford et al. 1989). Since 1945, annual Washington coast crab landings have fluctuated between 1.2 and 9.5 thousand metric tons per year (Fig. 2). The general life-history pattern of Dungeness crab along the Washington coast is as follows (Gunderson et al. 1990, Jamieson and Armstrong 1991). Females molt to maturity along the open coast, generally in the spring. Mating occurs at this time, but eggs are not extruded until the following winter. Eggs generally hatch between December and March, and larvae remain in the water column for a few months. Late-stage larvae are found onshore in late-spring and summer, where they settle to the bottom and metamorphose. Settlement occurs both in nearshore coastal waters and in estuaries; within estuaries, crab settle in both subtidal and intertidal habitats. Crab settling in intertidal areas may remain there during their first summer, but move into the subtidal zone in fall. Few older crab are resident in the intertidal, but move on and off the tidal flats with the tides (Stevens et al. 1984). Crab settling in nearshore waters may remain there for life, but there is evidence of some migration into the estuary between their first and second summers. Crab remain in estuarine subtidal areas for up to two years, but late-juvenile and early-adult crab leave the estuary before reproduction, which occurs mainly along the open coast. Both female and male crab reach sexual maturity at about 2 years of age, but males may not breed until age-3 or older (Butler 1960 and 1961, Hankin et al. 1989).

Methods

Model structure

The calculation of crab loss is driven by two variables: crab abundance (uncontrolled) and volume dredged (controlled). Both of these vary in both space and time. The two types of data are related through an entrainment function that describes the number of crab entrained by each type of dredging gear as a function of local crab density and volume dredged. Not all crab entrained are killed, so a second relationship describes the number killed as a function of crab age and dredge type. To apply the model, crab abundance is measured

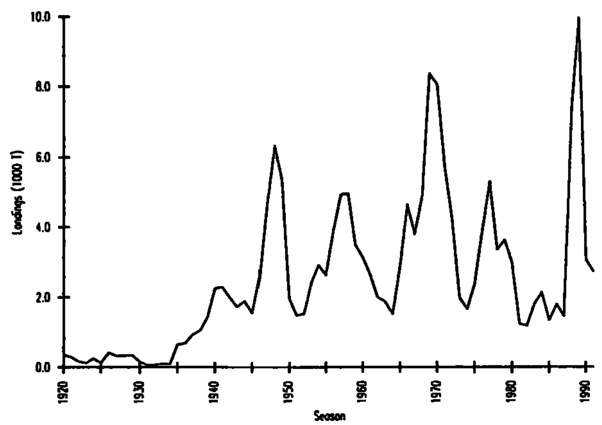

Figure 2
Historical landings in the Washington coastal Dungeness crab fishery. Sources: 1920–47, Cleaver (1949); 1948–50, Wash. Dep. Fish. (1951); 1951–87, Pac. Mar. Fish. Comm. (1989); 1988–91 are preliminary estimates (S. Barry, Wash. Dep. Fish., Olympia, pers. commun.).

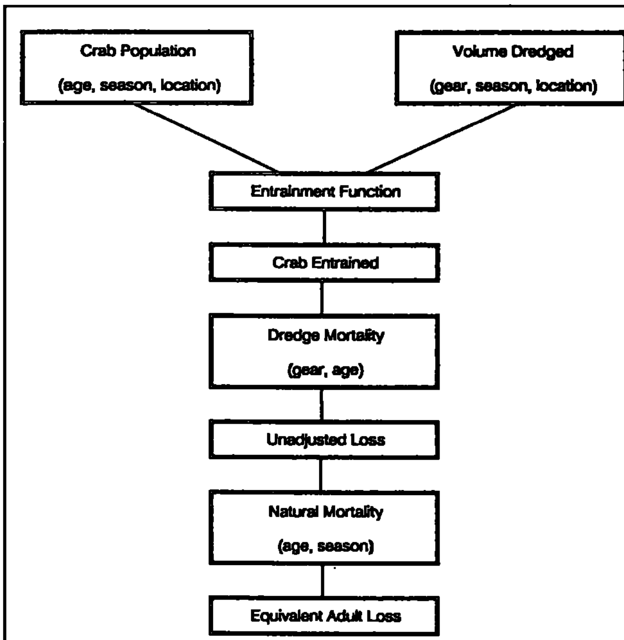

Figure 3
Flowchart of Dungeness crab adult loss model, showing main variables and structural categories (in parentheses).

as density stratified by age, season, and location. Dredging is described as the volume dredged by a particular gear in a location during a given season. Unadjusted loss figures are converted to equivalent adult loss by multiplying by the expected survival of crab from a certain age-class and season to adulthood. This approach is shown schematically in Figure 3, and described in detail below. Because we could not resolve older age-classes within our survey data, a crab was considered to reach adulthood in winter of its age 2+ year (i.e., approaching the end of its third year post-settlement).

Calculating losses in this manner requires an underlying concept of population dynamics and several simplifying assumptions. Creating a detailed model of local dynamics for a mobile benthic animal is difficult; there is continuous mortality and migration among habitats, the rates of which may vary with season, age, and locality. This may be summarized by the usual mass-balance equation for change in the population in a local area over a discrete time period:

$$N(t_1) = N(t_0) + R - M - E + I, \qquad (1)$$

where N is population abundance, t_0 and t_1 are two times, R is recruitment to the population (settlement), M is mortality, E is emigration, and I is immigration.

Mortality and migration rates are rarely known accurately (certainly not in our problem), so we have taken an empirical approach to defining population abundance. The approach is similar to, but simpler than, that taken by Boreman et al. (1981) for power plant entrainment in an estuary. The model is a discrete time, discrete age-population model with discrete habitat structure. To allow for seasonal changes in abundance or population structure, the year is subdivided into four seasons. Thus the population can be described as the numbers in various age-classes present in various habitat areas during particular seasons. In our model, abundance of any age-class in an area during a single time-step is taken to be the average abundance estimated from field surveys. We assume that all changes in abundance (i.e., mortality or migration) occur between time-steps, so that populations are constant throughout a step. This assumption introduces little error if the change during a step is small (less than about 10%), which will be true if time steps are relatively short and rates of change are relatively low. To meet this assumption in our application, we defined variable-length seasons of relatively constant population structure (see Data and Estimation section below).

The starting point for our calculations is estimated total crab density (D) for locations (l) and seasons (s), combined with age-class proportions (P). (Variables are fully defined in Table 1.) The second set of information needed for the calculation is the dredging schedule, expressed as volume dredged (V) by a specific gear type (g) in a specific location and season. For planning

Table 1
Model notation.

	Symbol	Description
Subscripts	a	age-class
	l	location
	s	season
	g	dredge gear
Population	D_{ls}	density
	P_{als}	age class proportions
	S_{as}	natural survival to adulthood
Dredging	V_{lsg}	volume dredged
Entrainment	e_g	entrainment rate
	m_{asg}	dredge-induced mortality proportion
Loss	E_{lsg}	total entrainment
	L_{alsg}	unadjusted loss
	EAL_{alsg}	equivalent adult loss

purposes, volume was measured as thousands of cubic yards (kcy) of dredged material (1 kcy = 765 m^3).

To obtain crab loss due to dredging from these two sets of information, we require crab entrainment rates (e), measured as numbers of crab entrained per unit volume dredged. Total entrainment (E) is

$$E_{lsg} = D_{ls} \cdot e_g \cdot V_{lsg}. \tag{2}$$

Postentrainment mortality (m), expressed as a proportion of those entrained, varies with gear type, age, and season. Age-specific loss (L) of crab in a single season, location, and gear combination will be

$$L_{alsg} = E_{lsg} \cdot P_{als} \cdot m_{asg}. \tag{3}$$

To compare the relative importance of losses from different age-classes, equivalent adult loss (EAL) for any season-location-gear combination is calculated as

$$EAL_{lsg} = \sum_a L_{alsg} \cdot S_{as}, \tag{4}$$

where S_{as} is the total natural survival to adulthood from age-class i in season k (assumed equal in all habitats). Total loss for the project is then

$$EAL_{tot} = \sum_{lsg} EAL_{lsg}. \tag{5}$$

Data and estimation

Population abundance Crab population surveys were conducted over a six-year period (1983–88) in Grays Harbor and along the adjacent coast. Stratified random sampling was done with a small beam trawl at biweekly or monthly intervals during spring and summer (May–September) with occasional sampling during fall and winter. From these surveys, crab densities were estimated for each stratum, and total population estimates were computed separately for Grays Harbor and the adjacent coast using the National Marine Fisheries Service BIOMASS program (Alaska Fish. Sci. Cent., 7600 Sand Point Way NE, Seattle, WA 98115), which uses standard stratified random survey statistical methods (Cochran 1962). Details of the survey design and population estimates can be found in Armstrong and Gunderson (1985) and Gunderson et al. (1990). In addition to the trawl surveys, intertidal crab were sampled in 0.25 m^2 quadrats at several locations within the harbor, and total intertidal population was estimated as described by Dumbauld and Armstrong (1987).

Growth and age-classes In general, age-class identification is difficult in crustaceans (Hartnoll 1982). The lack of retained hard parts prohibits direct aging techniques (such as scale analysis in fish), so age must be estimated from size. We relied on visual separations of age-classes in size-frequency plots from the population surveys, but molting and individual variability in growth obscure age-class modes except for young, rapidly growing crab. In all cases, young-of-the-year (age 0+) crab were easily identifiable as a separate size-group. Age 1+ size distributions sometimes overlapped older ages; in these cases, visual estimates of the separation point were supplemented by projecting growth from earlier observations. No reasonable separations could be made for older ages. For this reason, our analysis uses three age-classes: 0+, 1+, and >1+. Within Grays Harbor, we believe that most crab leave the estuary before their third year, so that almost all crab within the estuary identified as >1+ are actually age 2+, and this assumption is made in our analysis. Proportions in each age-class were then calculated from the total size-frequency distribution of each sampling stratum.

Definition of model seasons Seasons were defined to reflect important biological processes and major changes in crab abundance through the year. The spring season (April and May) reflects the start of settlement of the 0+ age-class and a period of migration into the estuary by age 1+ coastal crab; summer (June–September) is a period of continued settlement, rapid growth, and steady mortality for 0+ crab and relative stability for older age-classes. Fall (October–December) and winter (January–March) are periods for which we have little sampling data, but both are periods of general population decline, migration from intertidal to subtidal areas within the estuary by 0+ crab, and emigration from the estuary by older age-classes. Where data were lacking during fall and winter, values were projected from late-summer populations according to the trends in numbers observed in years for which winter data were available.

Definition of geographic strata The population survey design had four strata within Grays Harbor: Outer Harbor, North Bay, South Bay, and Inner Harbor (Fig. 1). The navigation channel passes through two of these (Inner and Outer Harbor), and crab densities within various reaches of the channel were assumed to be the average densities for the corresponding sampling strata. In fact, crab densities estimated within the channel during entrainment studies are quite comparable with those estimated from the corresponding strata of the regular surveys (Dinnel et al. 1986, Dumbauld et al. 1988, Wainwright et al. 1990). Thus calculations for Bar, Entrance, and South Reaches used crab densities for the Outer Harbor, while Inner Harbor values were used from Crossover Reach to Aberdeen Reach. Crab densities decline upriver, and South Aberdeen Reach was assumed to have no crab.

Mortality Mortality estimates were calculated by regressing logarithm of population abundance on age. This method was applied separately for early juveniles (age 0+) and for older juveniles and adults (age 1+ and older). Because substantial migration of 0+ crab to or from the estuary does not occur, mortality rates specific to Grays Harbor could be calculated for this age-group. To estimate mortality, total estuarine 0+ and 1+ populations were calculated from the six years of trawl survey data. Estimates for 0+ subtidal populations were supplemented with intertidal estimates to provide a complete representation of the estuarine population. Direct calculation of mortality requires analysis of a population with no recruitment or migration. Settlement had essentially ended by July of each year, so we chose July of the 0+ year as the starting point for calculations. During the 1+ year, migration begins near the end of the summer as crab leave the estuary. Because of this, we chose June of the 1+ year as the endpoint for estimating first-year survival. First-year mortality estimates were calculated for each of five cohorts (1983–87 year-classes).

Estimation of mortality for older ages is more difficult for two reasons: age-class separation is difficult and inaccurate, and migration to and from the estuary occurs. Because of these problems, a different approach was used. To reduce problems of migration, population estimates for the estuary and adjacent coast were combined. Age-class separations were made using an instar analysis technique (Armstrong et al. 1987, Orensanz and Gallucci 1988) to identify instar composition of the population. Instar abundances were then assigned to year-classes. To reduce errors from sampling and age-class identification, monthly abundance estimates were averaged over all year-classes, then averaged over months within each survey season to give a single estimate for each age-class (a):

$$N_a = \text{mean}(N_{amy}), \tag{6}$$

where N_{amy} is the abundance estimate for age a in month m of sample year y. Then survival from age a to a+1 was calculated as

$$S_{a,a+1} = \frac{\bar{N}_{a+1}}{N_a}. \tag{7}$$

Because a single strong year-class biases estimates calculated in this way, the very strong 1984 year-class was excluded. The calculated age-specific natural mortality rates were then combined to produce the survival schedule (S_{as} in Eq. 4) used to calculate equivalent adult loss from unadjusted loss.

Estimating entrainment rate Numerous studies have been conducted to estimate the rate of entrainment of crab by various kinds of dredges, and the subsequent damage and mortality to entrained crab (McGraw et al. 1988). Entrainment and subsequent mortality are discussed separately below.

A regression relationship was used to predict the entrainment rate (crab entrained/kcy dredged; e in Eq. 2) from trawl-based density estimates (crab/ha). This approach was used by Armstrong et al. (1987) and McGraw et al. (1988) to estimate entrainment rates for a hopper dredge. More data have been collected since those studies, so a new relationship has been calculated. Sampling during the entrainment surveys consisted of two parts: sampling of the dredged material stream aboard a hopper dredge, and concurrent trawl surveys within the channel section being dredged. During each survey, sampling occurred over a two- to three-day period and covered several stations within the navigation channel. For each survey, mean entrainment (crab per kcy dredged) and mean density (crab per ha) were calculated over all samples within each station. This provided a total of 14 points which were used to calculate the regression. Details of survey methods are given in McGraw et al. (1988).

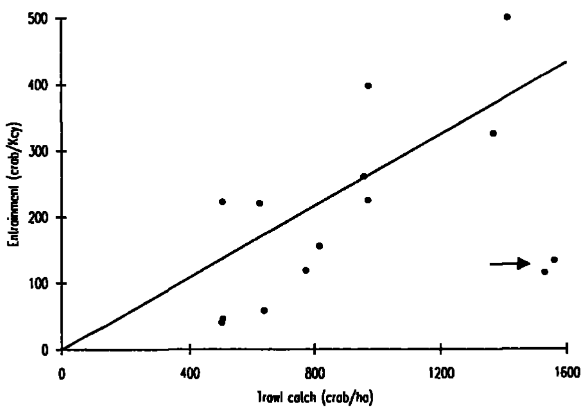

Figure 4
Relationship between trawl catch and entrainment of Dungeness crab by a hopper dredge. The line was fit by least-squares and non-parametric regression. Arrow indicates two outliers which were excluded from the least-squares regression.

To relate crab entrainment to crab density, several regression models were tried. The selection of a final model was based on both statistical measures of fit and biological reasonableness (i.e., an expectation that entrainment should increase with increasing crab density). First, a test for linearity ("XLOF" in the Minitab package; Minitab Inc., University Park, PA) was performed, and no significant nonlinearity was detected ($p>0.10$). Second, a linear least-squares regression was calculated; neither the slope nor the intercept were significantly different from zero for this model. However, this relationship was heavily influenced ("Cook's Distance Measure"; Weisberg 1985) by two points. When these two points were excluded, the best least-squares model was (Fig. 4)

$$Y = 0.27X, \tag{8}$$

where Y is entrainment by the dredge (crab/kcy), and X is trawl-estimated density (crab/ha). Finally, a nonparametric median-slope regression (Conover 1980) was calculated using all 14 data points. This method returned the same slope as the 12-point least-squares regression.

Entrainment for the other dredge types was calculated from this model based on relative entrainment factors given by Stevens (1981); entrainment by a pipeline dredge is assumed to be 100% of the hopper dredge value (this value is controversial, but is conservative), while a clamshell dredge entrains only about 5% of the hopper dredge value.

Table 2
Postentrainment mortality rates for Dungeness crab by age, season, and dredge type.

Dredge type	Age-class	Season	Size range (mm)	Mortality (%)
Hopper	0+	Apr–May	7–10	5
		Jun–Sep	11–30	10
		Oct–Dec	31–40	20
		Jan–Mar	41–50	40
	1+	Apr–Sep	51–75	60
		Oct–Mar	>75	86
	>1+	All	>75	86
Clamshell	All	All	All	10
Pipeline	All	All	All	100

Postentrainment mortality After entrainment, crab may be killed due to physical trauma during transport through pipes and pumps, burial under excessive sediment weight, or confined disposal in landfill by a pipeline dredge. Several estimates of postentrainment mortality (m in Eq. 3) have been made. For a hopper dredge, Stevens (1981) reported approximately 75% mortality, all sizes of crab combined. Armstrong et al. (1982) reported mortality rates by crab size for a hopper dredge, with 86% mortality for crab larger than 50 mm carapace width (CW) and 46% mortality for those smaller than 50 mm CW. Other studies indicate that hopper dredge mortality rates for small (<10 mm) 0+ age-class crab range from 1% to 5% (K. Larson, Portland Dist., U.S. Army Corps of Eng., pers. commun., 1987). Gross mortality observations were also made during later entrainment studies (McGraw et al. 1988, Wainwright et al. 1990), but these recorded only obvious mutilations and so underestimate total mortality. We adopted a set of size-dependent mortality rates for a hopper dredge based on these studies (Table 2).

Little information is available concerning mortality of crab entrained by a clamshell dredge. Stevens (1981) reported an overall mortality rate of less than 10%, which seems reasonable considering the operation of the gear. We have used a 10% mortality rate for a clamshell dredge for all age-classes. Because its effluent goes to confined upland disposal, 100% mortality was assumed for all crab entrained by the pipeline dredge.

Simulations Scheduling of dredge operations was based on engineering constraints, weather limitations, avoidance of salmon migration periods, and avoidance of seasons and areas with high predicted crab loss. To help in this planning process, loss rates (expressed as crab per volume dredged) were calculated for each area and each season, based on average seasonal crab densities and age-class composition.

Table 3
Hypothetical project scenarios for Grays Harbor, WA, showing volume to be dredged by each dredge type in each area and season.

Harbor section	Season	Dredge	Volume (kcy)
Scenario 1: Full confined disposal			
Outer	Jan–Mar	Hopper	1698
Outer	Apr–May	Hopper	1132
Outer	Apr–May	Hopper	330
Outer	Jun–Sep	Hopper	2800
Inner	Jun–Sep	Hopper	1000
Inner	Jun–Sep	Pipeline	434
Inner	Oct–Dec	Hopper	2036
Inner	Oct–Dec	Pipeline	2224
Inner	Jan–Mar	Hopper	1714
Inner	Jan–Mar	Pipeline	670
		Total	14,038
Scenario 2: Limited confined disposal			
Outer	Apr–May	Hopper	1462
Outer	Jun–Sep	Hopper	2800
Outer	Jan–Mar	Hopper	1698
Inner	Apr–May	Clamshell	771
Inner	Jun–Sep	Hopper	1000
Inner	Jun–Sep	Clamshell	579
Inner	Oct–Dec	Hopper	2036
Inner	Oct–Dec	Clamshell	778
Inner	Oct–Dec	Pipeline	374
Inner	Jan–Mar	Hopper	1714
Inner	Jan–Mar	Clamshell	826
		Total	14,038

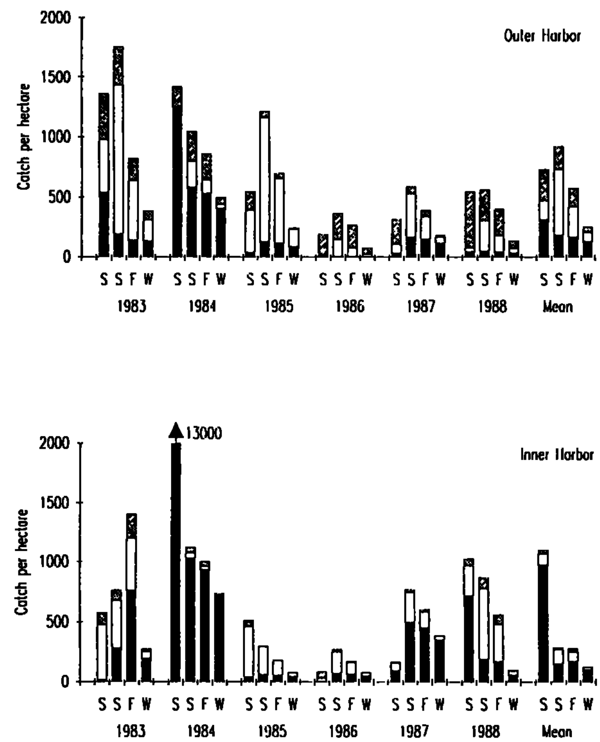

Figure 5
Seasonal abundance (catch per hectare) of Dungeness crab in the Outer and Inner Harbor strata of Grays Harbor, Washington, by age-class. Solid bars, age 0+; white, age 1+; hatching, age >1+.

Once project scheduling was determined, predictions of total crab loss were needed, which we calculated by simulating entrainment for planned construction scenarios. The scenarios we have used for calculating crab losses reflect the project as planned in 1987 (Table 3). There was some conflict between project costs and crab protection, particularly regarding the tradeoff between using gear that is economically efficient (hopper and pipeline) and that which minimizes loss (clamshell). Throughout most of the estuary, the efficiency of the hopper dredge makes alternatives uneconomic. In certain areas of the Inner Harbor, the pipeline dredge is economically most efficient but results in high post-entrainment mortality. The alternative dredge in those areas is a clamshell, which is generally more costly. To better evaluate this tradeoff, two scenarios are contrasted. Scenario 1 includes full use of a pipeline dredge where it is most effective; in Scenario 2, a clamshell dredge is substituted where feasible. Table 3 shows volumes dredged under each scenario by gear type, location, and season.

As initially planned, construction was to occur over two calendar years, extending through seven seasons. To simplify calculations, we compressed the project into a single model year (from spring of a given calendar year through winter of the next), and calculated entrainment and losses for each scenario separately based on each of the six years of survey-based crab abundance estimates. This produced a set of 12 (six years by two construction scenarios) model runs.

Because the project was revised in several ways since these calculations were made, results presented here do not reflect actual expected losses resulting from the project, and are presented only to illustrate the method.

Results

Population parameters

Age-class abundance Densities of crab in the Inner and Outer Harbor strata varied considerably among years and seasons (Fig. 5). Average seasonal total density ranged from 73 ha^{-1} to 13,000 ha^{-1}. Age 0+ crab were most abundant in 1984, and were usually more abundant in the Inner Harbor. Older crab were more

Table 4
Estimates of instantaneous mortality (Z) and annual survival (S) for age 0+ Dungeness crab, Grays Harbor, WA.

Year-class	Z (yr^{-1})	S (%)
83	3.4	3.4
84	2.2	11.5
85	3.5	3.0
86	1.6	19.8
87	1.9	15.2
Average	2.5	8.1

Table 5
Estimates of instantaneous mortality (Z) and annual survival (S) for older age-classes of Dungeness crab, Grays Harbor, WA, and adjacent coast combined. Estimates are for July–July, average for several years.

Age	Z (yr^{-1})	S (%)
1+ – 2+	1.6	19.5
2+ – 3+	0.8	45.0
3+ – 4+	1.0	38.0

Table 6
Survival schedule: percent of Dungeness crab surviving from each season to midwinter (15 Feb.) of the 2+ year.

		Age-class		
Season	Midpoint	0+	1+	2+
Apr–May	30 Apr	0.87	10.7	53.2
Jun–Sep	31 Jul	1.65	16.0	64.9
Oct–Dec	15 Nov	3.40	25.5	81.9
Jan–Mar	15 Feb	6.35	38.0	100.0

abundant in the Outer Harbor, where they reached peak densities in the summer season.

Mortality Estimated instantaneous mortality rates for age 0+ crab within Grays Harbor ranged from 1.6 to 3.5 yr^{-1}, with a mean of 2.5 yr^{-1}, corresponding to an annual survival of 8.1% (Table 4). For older crab, estimated mortality rates (Eq. 7) decreased to age 3+, then increased slightly between ages 3+ and 4+ (Table 5). These two results were combined to derive the seasonal survival schedule (Table 6) used in the model.

Gear and season comparisons

The results of gear/season comparison simulations are presented in Figures 6 and 7. These data show the strong contrast between the pipeline and clamshell dredges: the clamshell dredge has negligible impact. Comparing the unadjusted losses (Eq. 3) with age 2+ equivalent losses (Eq. 4) shows the relative unimportance of 0+ crab. Also notable are the high age 2+ equivalent losses in the Outer Harbor during summer and fall, when there are concentrations of age 1+ and older crab in this area (Fig. 5).

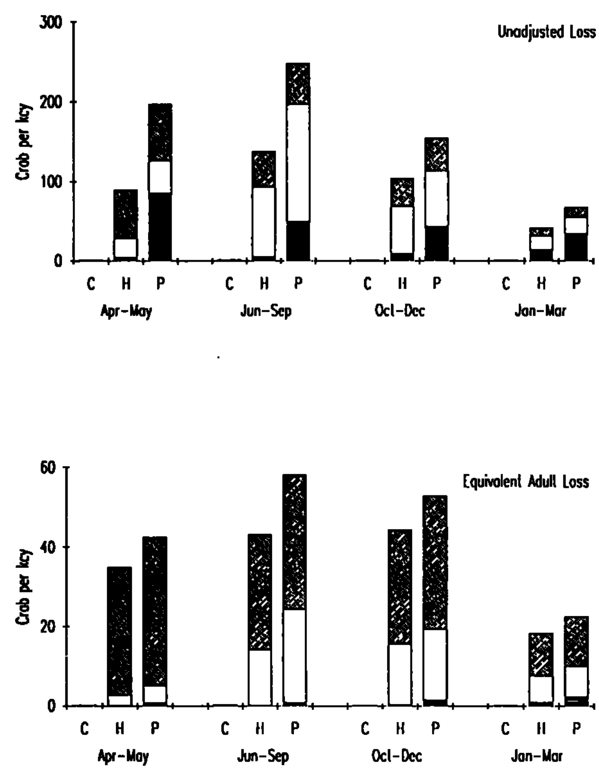

Figure 6
Entrainment rates of Dungeness crab by season and dredge type for the Outer Harbor, by age-class. (upper) Unadjusted losses; (lower) age 2+ equivalent losses. Dredge types: C = clamshell, H = hopper, P = pipeline. Age-classes as in Figure 5.

Impact estimates

Calculations of total age 2+ equivalent loss (Eq. 5) for the two project scenarios are shown in Figure 8. As expected, Scenario 1 (full use of the pipeline dredge with confined disposal) shows higher losses than Scenario 2. For both scenarios, a large part of the total loss occurs during the June–September season, due to large volumes being dredged in the Outer Harbor where older crab are concentrated at this time. The results indicate strong year-to-year variation in

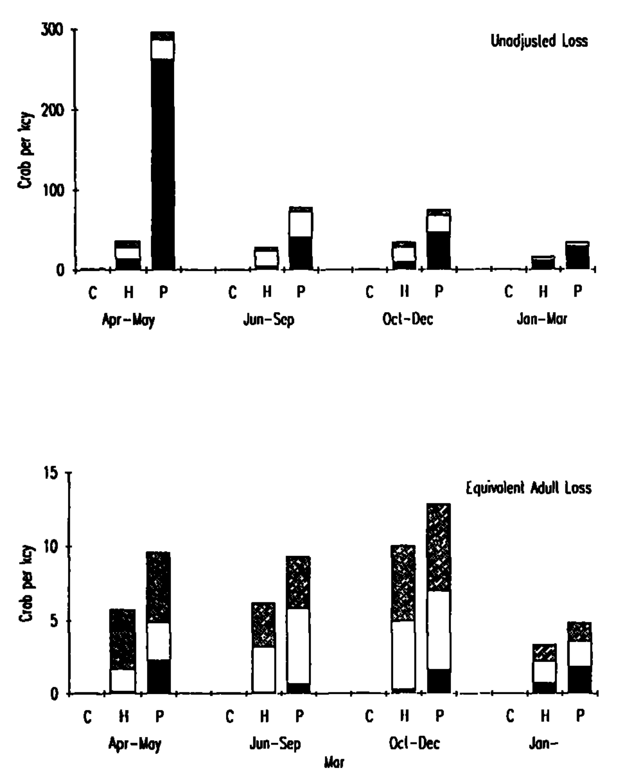

Figure 7
Entrainment rates of Dungeness crab by season and dredge type for the Inner Harbor, as in Figure 6.

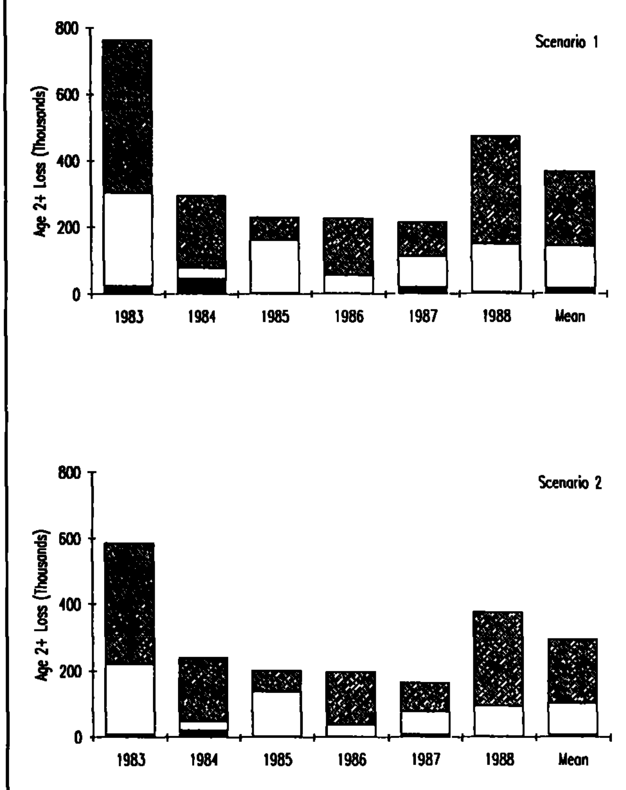

Figure 8
Total estimated age 2+ equivalent losses for hypothetical dredging in six years for two project scenarios. (upper) Full use of confined disposal; (lower) limited confined disposal. Age-classes as in Figure 5.

impacts, with 1983 construction resulting in impacts nearly three times the average for the other years. This is apparently because 1983 followed two years of strong settlement, as evidenced by the high abundance of both age 1+ and >1+ crab in that year (Fig. 5; see also Gunderson et al. 1990). This emphasizes the importance of population monitoring during construction to accurately assess impacts.

Discussion

Gear and season comparisons made with DIM provided several results which were subsequently used to schedule construction gear, season, and location combinations so as to reduce crab losses. As expected, the clamshell dredge (which moves slowly and does little mechanical damage to organisms) had insignificant impact in all seasons and areas. Comparing pipeline and hopper dredge effects, our initial impression was that, with confined disposal (resulting in 100% loss of all age-classes), the pipeline dredge would cause extremely high losses relative to the hopper dredge. This is true when one considers the unadjusted losses (Figs. 6A and 7A). However, when viewed on an equivalent adult loss basis (Figs. 6B and 7B), the pipeline dredge loss rate is only 10–50% higher than that of the hopper dredge. The equivalent adult loss viewpoint was also important in seasonal comparisons, especially in the Inner Harbor (Fig. 7) where unadjusted loss was highest in spring, but equivalent adult loss peaked in fall.

During any modeling endeavor in applied ecology, certain decisions must be made to limit the scope and applicability of the model. Many decisions are made simply on the basis of information or time available, while others reflect the biases and experiences of the authors. One of the major decisions in this project was the choice between predicting short-term losses via the equivalent adult loss approach, or accounting for potential longer-term losses due to reduction of the local reproductive stock via "production foregone" (Rago 1984) techniques. For local, short-term entrainment to have longer-term population effects requires a strong influence of current stock size on future recruitment.

For Dungeness crab, there is little evidence of stock-dependence. In fact, it is not clear whether a local stock, such as that in Grays Harbor, is self-reproducing or depends on larval drift from other areas. For this reason, we chose to use only short-term loss predictions.

The choice of slope for the regression of crab entrainment on trawl catch will strongly influence model results. We gave long consideration to the choice of regression models. Problems arise because there are few data points and large measurement errors associated with both variables. Costs of sampling (which involved simultaneous operations of a specially modified hopper dredge and a chartered trawler) prohibited any increase in data quantity or precision. Initially, we chose to use least-squares regression (LSR) with its underlying assumptions of normal errors with equal variances. There are two forms of LSR in common use: predictive LSR which assumes that all error is in measurement of the Y (dependent) variate, and functional LSR which incorporates errors in both X and Y variates. In the overall context of DIM, the entrainment regression serves the role of a calibration curve predicting entrainment from a set of observed trawl catches. For this reason, we used a predictive regression conditional on the observed trawl catches. (This implies that the result is not generalizable to any other method of crab density estimation, but such generalization is not needed here.) Two outliers were dropped from the LSR analysis; both points were from the same station in different years, and both were influenced by one or two extremely high trawl catches. Because we were not entirely satisfied with the assumptions of the LSR analysis, the data was reanalyzed using a nonparametric regression technique which is robust to nonnormality, inequality of variances, and errors in measurement of the X variate. Because this analysis agreed with the final LSR model (Eq. 8), we accepted that model as the most reasonable.

Another limitation was our inability to reliably distinguish age-classes beyond 1+ and obtain mortality estimates for older age-groups. Because of this, we stopped our calculations at age 2+, but there is a strong desire to relate the results to fishery stocks with recruitment at 3–5 years of age. It is possible to perform some rough calculations of actual impact to fisheries, if we are willing to make some assumptions. Using Scenario 2 (limited confined disposal) as an example, estimated age 2+ equivalent losses ranged from 166 to 587 thousand crab (Fig. 8). The fishery harvests males only, so with a 50% sex ratio these numbers become 83–298 thousand age 2+ male crab lost. To relate these to the fishery, we need to know survival from age 2+ to recruitment. We have rough estimates of mortality from age 2+ to 3+ and from age 3+ to 4+ (Table 6) calculated from the trawl survey data set. These estimates are confounded with the decline in gear efficiency with crab size, and so are probably underestimates of true survival. They also depend on tenuous assumptions about size-at-age. Accepting these estimates and assuming the bulk of the fishery recruits at age 3+, our estimates of age 2+ loss correspond to losses to the fishery of 37–134 thousand age 3+ male crab. As exploitation rates are quite high (~70–90%; Methot and Botsford 1982), these numbers can be related directly to annual catch. The ten-year average catch for the Washington coast has been about 3000 metric tons, which corresponds to 3.3 million crab (average individual weight of 0.9 kg). So, losses for this hypothetical scenario would be on the order of 1–4% of the average annual catch by the Washington coast fishery.

The model was limited by several other factors, particularly problems of data quality and parameter estimates. Primary among these was lack of data on beam trawl efficiency and size selectivity (Gunderson and Ellis 1986). We have implicitly assumed that the trawl sampling was 100% efficient for all sizes of crab, which is certainly not the case. The gear was designed for capturing juvenile crab, and we believe it to be relatively efficient for juvenile sizes, but crab approaching legal size are able to avoid or escape the small net. For estimating absolute numbers entrained, this is not a problem because the entrainment function is essentially a calibration of entrainment against trawl catch, regardless of trawl efficiency. However, to the extent that gear efficiency is below 100%, we underestimate total populations within the estuary. Calculations of entrainment as a proportion of the local population are thus biased upward. Trawl efficiency also affects natural mortality rate estimates, to which equivalent adult loss calculations are extremely sensitive.

Overall, DIM has proved useful even with its limitations. In project planning, the model allowed scheduling gear and work seasons to reduce impacts on the crab population, and provided some quantitative predictions of loss on which to base mitigation programs. DIM is now being used in conjunction with crab survey data gathered during construction to estimate actual crab losses and to fully define levels and type of mitigation. Beyond these intended uses, the model served to focus concerns about crab impacts, which tended to be somewhat ill-defined, onto specific questions of data quality and reliability of predictions, providing all sides a common basis for argument.

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