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Ecological assessment criteria for restoring anadromous salmonid habitat in Pacific Northwest estuaries

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Abstract

Restoration of estuarine habitats is essential for the conservation and recovery of depressed Pacific salmon populations. However, assessing the functions of recently restored habitat poses a number of problems because of the transitory occurrence of salmonids in any one location. We propose assessment criteria and metrics that are based on the habitat's *capacity*, *opportunity*, and *realized function* to enhance survivability of juvenile salmon. Because of the paucity of data relating capacity and opportunity attributes to realized function (e.g. growth, consumption rate, survival), there continues to be a need for manipulative experiments to assess the developmental status of restoration sites. Such a self-monitoring approach of letting the fish diagnose the ecological state of restoration would effectively address the small-scale, site-specific assessment goals and criteria, but ignores the larger-scale issues relating to the ability of diverse salmon species and life histories to occupy estuarine habitat landscapes. If coastal restoration is going to contribute the recovery of anadromous salmonid populations, a landscape perspective is fundamental to restoration planning, implementation, and particularly assessment. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Restoration; Habitat; Anadromous salmonids; Pacific Northwest; Assessment criteria

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1. Introduction

In the Pacific Northwest, dramatically reduced and altered estuarine landscapes have been associated with the declining salmonid populations. As a result, goals and assessment of estuarine habitat restoration are often based on reparation of historically impaired salmonid (Pacific salmon and related *Oncorhynchus* spp.) habitats. Estuaries constitute highly variable, large-scale ecotones through which anadromous salmonid stocks must pass as outmigrating juveniles and returning adults. In particular, passage and rearing of juveniles (particularly ocean-type chinook, *O. tshawytscha*, and chum salmon, *O. keta* fry) in estuarine habitats are often viewed as cornerstone phases of their life history when physiological adaptation, foraging, and refugia from predators or adverse physicochemical stressors are critical (Healey, 1982; Simenstad et al., 1982). The degree to which anadromous salmonids are actually 'dependent' upon estuarine habitats is still debated and remains to be tested conclusively (Levings,

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1984; Levy, 1984; Simenstad, 1997). However, patterns of juvenile salmon growth and survival in different estuarine habitats and conditions argue that occupation of estuarine habitats contributes to the survival and fitness of juvenile salmon throughout their life history (Reimers, 1973; Levings et al., 1986).

It is likely that the loss of more than 50% of the historical estuarine wetland area in this region has contributed to the decline of anadromous salmonids (Simenstad et al., 1982; Simenstad, 1997; Levings et al., 1986; Thom, 1987). Consequently, enhancement and restoration of salmon habitat is a prevalent goal guiding regulatory mitigation and, to some extent, non-regulatory restoration of estuarine wetlands (Simenstad and Thom, 1992). Unfortunately, estuarine restoration for juvenile salmonid habitat has been to a large degree based on a ‘build it and they will come’ supposition that ignores the need for critical evidence demonstrating that restoration of habitat actually contributes to the *support* of juvenile salmon. It is assumed that the increases in salmonid production will occur quickly, but whether occupation of a restored or rehabilitated[1] habitat by juvenile salmonids actually results in decreased mortality has to our knowledge never been assessed.

While various metrics of ‘use’ by juvenile salmon (e.g. fish occurrence and abundance) are commonly employed to assess relative success, most assessment and monitoring approaches are short-term and fail to determine either the production of juvenile salmon or the underlying responsible mechanisms. The absence of any long-term prognosis for Pacific Northwest salmonid habitat restoration leads to ambiguity as to its potential contribution to salmonid population recovery, and prevents the feedback required for adaptive management in the redesign of future restoration. In this study, we (a) examine the basic premises behind habitat restoration and assessment for juvenile salmonids; (b) evaluate common and alternative assessment criteria; (c) cite examples of insightful metrics of the status and mechanisms of estuarine juvenile salmon habitat restoration; and (d) propose some fundamental changes to our routine approaches of habitat assessment. We describe four estuarine restoration sites where we have placed particular focus on their status as juvenile salmon habitat (Table 1), and posit that, for restoration sites to contribute the recovery of salmonid populations, they must be self-sustaining and assessments must be long-term (Parker, 1997). The information required to restore Pacific salmonid habitat must address six major points of uncertainty (In enumerating these we have not lost sight of the fact that the guiding focus must be much broader than a single species.),

1. specific estuarine habitat requirements of juvenile salmon remain relatively unquantified, and undependable as design or assessment parameters;
2. there are no models or measurements of applicable successional habitat development in estuaries from this region that could serve as templates of functional equivalency trajectories;
3. the assessment time frame of restoration has been too short to identify predictable endpoints in wetland development;
4. the use of reference sites is essential, but they are also inherently variable;
5. survival and growth of salmonids using restored habitat are seldom evaluated; and
6. the assessment of restored estuarine habitats needs to be expanded to the landscape scale and placed in the context of the entire freshwater–ocean continuum.

2. The rationale for juvenile salmonid habitat restoration

The few rigorous studies that have tested estuarine ‘dependence’ by measuring survival of juvenile salmon (e.g. Reimers, 1973; Levings, 1984; Levings et al., 1986) generally have not linked

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[1] Although we use the terms ‘restored’ or ‘rehabilitated’ habitats, we do not imply that they have achieved equivalence to natural-functioning habitats but simply that restoration of tidal flooding, soil development, fish access, and other natural processes could be promoting redevelopment of a natural community.

Table 1
Example of functional assessment criteria for juvenile salmon support at four estuarine habitat restoration sites in Pacific Northwest

Site	Location and restoration date	Landscape setting	Salmonid spp.	Diet attributes	Reference sites	Success criteria	References
Gog-Le-Hi-Te	Puyallup River estuary, Puget Sound, 1986	Urban-industrial, oligohaline-tidal freshwater, excavated fill	Chum, chinook, coho, steelhead	Emergent insects, benthic invertebrates	None in proximity (Nisqually River estuary)	Fish presence, density and diet; benthic invertebrate density; fish growth, residence time and diet overlap with invertebrate assemblages	Shreffler et al. (1990, 1992), Simenstad and Thom (1992, 1996), Thom et al. (1987, 1988a,b, 1990, 1991)
Created slough	Chehalis River estuary, Grays Harbor, 1990	Natural, oligohaline, tidal-freshwater slough; excavated forested wetland	Chum, chinook, coho, steelhead	Riparian and emergent insects, benthic invertebrates, macrozooplankton	Natural slough	Fish presence, density and diet; insect and benthic invertebrate composition and density; fish growth and diet overlap with invertebrate assemblages and reference site	Miller (1993), Miller and Simenstad (1994, 1997), Simenstad and Thom (1992), Simenstad et al. (1992, 1993, 1997a)
Terminal 105	Duwamish River estuary, Puget Sound, 1994	Urban-industrial, mesohaline; excavated fill	Chum, chinook	Riparian insects, benthic invertebrates	Relict emergent wetland	Fish presence, density and diet; insect and benthic invertebrate composition and density	Cordell et al. (1994, 1996, 1997)
Spencer Island	Snohomish River estuary, Puget Sound, 1994	Agricultural-natural, oligohaline; breached dike	Chum, coho, chinook, steelhead, Dolly Varden	Riparian and emergent insects, benthic invertebrates	Natural, undiked wetland	Fish presence, density and diet; insect and benthic invertebrate composition and density	Cordell et al. (1998)

them to specific habitats or habitat attributes. Thus, the magnitude and *significance* of salmonid associations with specific habitat attributes have been purely inferential, rather than empirical or mechanistic. The punctuated demographics of juvenile salmon migration patterns and habitat use in the estuary varies with the timing of their emigration from watersheds, their position along the estuarine gradient, species and life history composition, and density. In this respect, estuaries act as both the filter and the modulator, selectively advancing some components of the population while retaining others, both of which can involve habitat interactions. The extreme variation in salmon growth and mortality in the ocean underscores our need to know the role that estuarine habitat quantity and quality play in subsequent ocean survival. Therefore, our approaches to functional assessment of estuarine habitats should consider not only how various life history stages will use the habitat, but also how habitat fits into the various life history transitions that juvenile salmonids make as they pass through the estuary.

Fundamental premise: *Habitat associations of juvenile salmonids depend on both species and life history*

This premise is important to any examination of estuarine habitat used by juvenile salmonids because species and life history diversity are reflected in variation in the mode and extent of habitat use. In the Pacific Northwest, salmonids co-evolved with the emerging coastal habitats. Post-glacial variations in river flows, sea level and landscape geomorphologies as well as biogeographic variation have promoted diverse salmonid population structures that are adapted to unpredictable regional factors, such as climatic effects on river flow, ocean production, and predators (Healey, 1991; Salo, 1991; Simenstad et al., 1997b). Juvenile salmon estuarine life histories reflect both genotypic characteristics and tactical responses to estuarine conditions and, as a consequence, the optimum strategy is to maximize life history diversities that can accommodate the range in those conditions.

Physiology, behavior, ontogeny, and stochastic environmental events all influence the type, duration, and reasons for estuarine habitat occupation by juvenile anadromous salmon. For instance, different salmon species of the same size often demonstrate distinct preferences for particular prey taxa, as in the case of chum fry for harpacticoid copepods and chinook salmon for gammarid amphipods (Simenstad et al., 1982), associated with different salinities, vegetation, substrates, and other habitat characteristics. However, these preferences shift with the ontogeny of the juvenile salmons' passage along the estuarine gradient in accordance with the changing habitats and invertebrate assemblages.

Thus, based on the variability in interactions of anadromous salmonids and their diverse life histories with the estuarine habitats, restoration goals and assessment criteria must address several important issues, recognizing that the coastal environment is only one portion in the continuum of salmonid use,

1. What are the salmonid species and life history stages that are expected to occur in the system as a whole, and which life history stages would be expected to utilize the restored habitat? This should not necessarily be based on the present state of salmonid populations because restoration of watershed habitat and rebuilding of stocks through other mechanisms could diversify future populations. Historic salmonid population structure is the preferable baseline.
2. What species and life history stages will utilize the restored habitat based on its location in the coastal landscape and resulting physical and biotic attributes?
3. What is the goal of the restoration, relative to salmonid refuge and/or foraging, and what are the species and life history stage-specific attributes being enhanced (e.g. large woody debris, low-energy channel, riparian insect production, benthic invertebrates)?

Fundamental premise: *Achieving goals for juvenile salmon habitat restoration is contingent on uncertain endpoints and pathways.*

One major dilemma in assessing the ecological function of restored estuarine habitats is that restoration sites take longer to reach maturity than the typical timespan of monitoring commitments (if monitoring is funded at all) or dedicated research. Therefore, can functional equivalency trajectories (Simenstad and Thom, 1996) be measured to predict long-term trends in success or failure? Even if they pass through natural successional patterns, achievement of functional equivalency with comparable target habitats may take decades. While some habitat functions, such as avifauna use, are exceedingly responsive (often depending upon the landscape context of the restoration site; e.g. Simenstad and Thom, 1996), attributes that contribute to fish production are often contingent on exceedingly slow or delayed processes. For example, the development of estuarine marsh invertebrate assemblages is generally regulated by or coincident with marsh soil development and detritus trapping, and benthic invertebrate assemblages are often shaped by complex predation and competition processes that occur over the long-term (Moy and Levin, 1991). In addition, early developmental stages of an estuarine community may be much more prone to disruptive disturbances and intrusions by exotic species than are later, more mature stages. To a large degree, information on the long-term fate of restored, and constructed, estuarine habitats is inadequate and full of uncertainty.

Restoration goals that are species- and life history-specific often assume a particular, stable habitat ‘endpoint’, such as a mature marsh or dense eelgrass meadow. In fact, over the long-term, restored habitats will typically develop and readjust in response to both abiotic and biotic processes and, depending upon the temporal scale of consideration, even late successional habitats may be unstable. Even under optimum circumstances, we are not sure they will follow predictable developmental trajectories (Brinson and Rheinhardt, 1996; Simenstad and Thom, 1996; Zedler, 1996), which depend upon the scale of external influences on the types, frequencies, and magnitudes of processes driving the patterns and rates of change within the habitat (Pickett et al., 1987; Parker, 1997). For example, expected sequences of vegetation and invertebrate recruitment, and subsequent juvenile salmon utilization of vegetation structure for refuge and invertebrates as prey, are contingent upon both initial conditions (e.g. excavated tidal elevations) and landscape processes (e.g. inflow transport of suspended sediment and plant and invertebrate propagules).

Most of the objective approaches in determining trends and status of habitat restoration sites require establishment of ‘reference’ levels for the relevant assessment criteria. In order to account for or avoid the confounding effect of natural spatial and temporal variability, reference assessment criteria must be derived for undisturbed habitats, which is not necessarily a trivial problem (Brinson and Rheinhardt, 1996). For example, a comparable reference site for a brackish marsh restoration site (Gog-Le-Hi-Te) in the Puyallup River estuary (Table 1) was nonavailable within that system, and comparisons of critical attributes, such as above- and belowground biomass of *Carex lyngbyei*, to data from natural marsh sites in other estuaries were complicated by high variation at these reference sites (Simenstad and Thom, 1996). Even, where seemingly appropriate reference sites exist, landscape-level changes can affect comparability. Since 1993, we have been accumulating data for reference intertidal habitats in the Duwamish River estuary (Table 1) that document both intra- and interannual variability in comparison to several restoration sites in the estuary (Cordell et al., 1994, 1996, 1997). However, these reference sites are relict patches within a highly industrialized landscape and subject to various stressors that might compromise their applicability.

To a large degree, developmental trajectories are predicated on initial conditions; the further initial conditions are from a ‘mature’ steady state, the longer it will take a system to approach or reach a late successional stage (Mitsch and Wilson, 1996). It is apparent that early geomorphic and ecological processes will determine the rate if not the outcome of development. In many cases, supplanting important natural processes such as sediment accretion, soil development, and plant recruitment by soil amendment, plant transplantation, weed control, or other eco-engineering approaches has been utilized as a means of ‘jump-starting’ initial conditions. The varying degrees of success by using this strategy suggest that there is an inherent danger in designing, constructing initial conditions, and assessing the criteria of habitat and community structure based on a preferred endpoint rather than allowing extant processes to 'self-design' developmental trajectories toward a natural endpoint (Gibson et al., 1994; Mitsch and Wilson, 1996). It has yet to be demonstrated that such 'designer habitats' promote self-sustaining habitat attributes that will not require long-term maintenance or re-engineering. In dynamic conditions, such as estuarine habitats, adoption of community functions as a restoration goal is likely to be more appropriate than attempting to restore community structure per se (Palmer et al., 1997). Even supposedly self-designed restoration can pose dilemmas if expectations and goals do not take into account the time, processes, and successional stages that must transpire before approaching a mature system. For another example, an estuarine marsh restoration site in the Salmon River estuary, coastal Oregon, deviated from its original goal because subsidence of the diked marsh promoted rapid recruitment of a low (elevation) marsh rather than the target of high marsh community (Frenkel and Morlan, 1991).

Fundamental premise: *Restoration should consider anthropogenic change in the processes that produce variation in estuarine habitat structure and function in supporting juvenile salmon.*

Restoration of estuarine habitats is particularly 'historically contingent' (Parker, 1997). Ecosystem processes that influence patterns and rates of a restored habitat's development (e.g. salinity distribution, freshwater flow regime, disturbance, and exotic species recruitment), as well as juvenile salmonid occurrence have often been altered historically. Historic templates are often inappropriate because of the contemporary environmental regime (Pickett and White, 1985) is significantly different from the historical environmental regimes (Parker, 1997). Restoration of historic salmonid habitat structure and location may be just as much contingent on restoration of critical processes, such as natural freshwater flow hydroperiods, sediment transport and accretion, and disturbance sources, frequencies and intensities of disturbance as on the removal of anthropogenic modifications and stressors that caused the habitat loss or degradation.

In our assessment of restoration sites in the Pacific Northwest, we have learned some important lessons related to these premises. For example, at the Gog-Le-Hi-Te wetland, extensive sedimentation of excavated tidal channels, mortality and retreat of transplanted sedge (*C. lyngbyei*), and successful natural recruitment of cattail (*Typha latifolia*) differed greatly from the 'engineered' concept, and repeated, intensive maintenance would be required to retain the deeper, original design (Simenstad and Thom, 1996). Accretion of a natural tidal platform and formation of a complex tidal channel system suggest that natural processes are promoting the development of an estuarine marsh community appropriate for the current system, and that functions supporting juvenile salmon will be self-sustaining even if not as 'designed'. Similarly, a number of mitigation projects in the Pacific Northwest have included constructed habitat designs using 'fish rock' (large, angular gravel that has been demonstrated to support high densities of preferred prey organisms of juvenile salmon when colonized by epiphytic algae), although it is not a natural attribute of oligohaline or mesohaline reaches of estuaries and will be rapidly subsumed by accretion of fine sediments in most locations.

Developing goals and assessment criteria that are based on habitat function rather than structure accommodates the fact that functions supporting juvenile salmon in developing (and likely mature) restoration habitats will change with succession and disturbance. Over the past decade, our experiences and observations from restored estuarine habitats suggest that habitat attributes (e.g. tidal channel density, vegetation, benthic invertebrates and insects) often become more diverse and perhaps more resilient as tidal elevations increase, although this varies by salinity regime and specific invertebrate taxa. This suggests that early successional habitats would more directly support the salmon foraging on mudflat organisms (e.g. harpacticoid copepods, gammarid amphipods), while later stages would benefit those species foraging on emergent marsh insects, at the same time that access for foraging is being gradually reduced from the mudflat plain to the tidal channel edge (Fig. 1). Coincidentally, the habitat's export of detritus and prey organisms (e.g. emergent insects) to other reaches of the estuary increases and predation may decline as the marshes geomorphology and community mature.

3. Assessing restoration success

Depending upon species and size, juvenile salmonids may occupy estuaries for as little as a few hours to more than 12 weeks (Healey, 1982; Simenstad et al., 1982; Groot and Margolis, 1991). This further compounds the customary challenges of assessing habitat use by resident fish (e.g. Minello and Zimmerman, 1992; Minello et al., 1994; Kneib, 1997a; Rozas and Minello, 1997). Because of their relatively episodic occurrence, presence or densities of juvenile salmonids are only superficial indicators of habitat function. Fish occupy the matrix of estuarine habitats rather than a particular habitat. Thus, in short of debilitating water quality or absolute blockage to access, estuarine habitats are viable migratory pathways for juvenile salmonids irrespective of their value for enhancing survival. However, evaluation of juvenile salmon growth and survival attributable to a particular habitat or habitat quality is difficult and exceedingly labor-intensive. Estimation of salmon survival in relation to anyone factor poses two conundrums, (1) the many phases and specific factors that cumulatively contribute to the survival as returning adults are complex and generally unquantified; and (2) total survival cannot be determined until many years of returning adults from one brood year are accounted for.

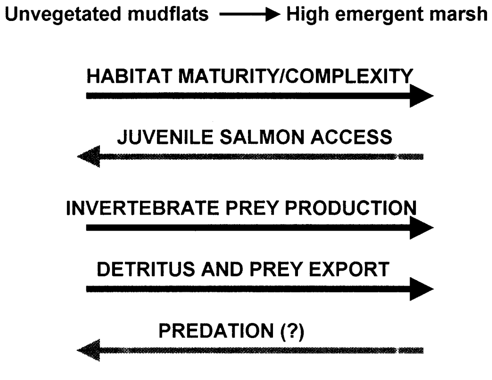

Fig. 1. Change in habitat function with increasing successional development of Pacific Northwest estuarine wetlands.

Ecological and structural attributes of estuarine habitats that promote salmon survival offer potentially more appropriate and tractable assessment criteria. We advocate by using measures directly relatable to ecological and physiological responses of juvenile salmonids to restored estuarine habitats as the decisive test of habitat recovery. We discuss three categories of habitat assessment metrics for these criteria — capacity, opportunity, and realized function.

Capacity metrics include habitat attributes that promote juvenile salmon production, through conditions that promote foraging, growth, and growth efficiency, and/or decreased mortality. Examples of capacity metrics include,

- productivity measures of availability and quantity of selected invertebrate prey;
- physicochemical conditions that maintain these prey communities;
- salinities and temperatures that promote high assimilation efficiencies; and
- structural characteristics that provide protection from predators.

Although their diet composition certainly varies depending upon position along the estuarine gradient, certain invertebrate prey taxa (e.g. dipteran fly [chironomid] larvae and adult insects such as aphids; gammarid amphipods such as *Corophium* spp.; harpacticoid copepods such as *Harpacticus uniremis* and *Tisbe* sp.), appear consistently as prominent dietary components as juvenile salmonids migrate through estuarine habitats (Sibert and Kask, 1978; Simenstad et al., 1982). This relatively predictable foraging behavior can be diagnostic of the prey production in restored habitats. For example, monitoring of juvenile chum and fall chinook salmon naturally accessing or experimentally released into the Gog-Le-Hi-Te wetland (Shreffler et al., 1992) indicated that the dominant prey within the wetland were primarily benthic or epibenthic organisms (e.g. chironomid larvae, the gammarid amphipods *Corophium salmonis*, *C. spinicorne* and *Eogammarus confervi-*

Table 2
The importance of chironomid insects in the diets of juvenile chum and fall chinook salmon entering (inlet) and occupying (outlet, beach seine) the Gog-Le-Hi-Te wetland; the percent of total index of relative importance (IRI) is broken down into chironomid life history stages (larvae, pupae, adult) (from Shreffler et al., 1992)

Year	Source	Species	Chironomids			
			Total IRI (%)	Larvae (%)	Pupae (%)	Adult (%)
1987	March	Chum	60	58	15	27
		Chinook	42	41	22	37
	April	Chum	90	62	18	20
		Chinook	57	32	63	5
	May	Chum	96	56	11	33
		Chinook	53	18	65	17
1988	Inlet	Chum	64	40	7	53
		Chinook	46	30	6	64
	Outlet	Chum	90	60	3	37
		Chinook	70	45	6	49
	Beach seine	Chum	50	80	10	10
		Chinook	57	69	17	14

colus, and the mysid *Neomysis mercedis*) that could be attributed to the restored system's production capacity, as compared with zooplankton and drift insects that could have been produced in either the marsh or the river. In particular, diets of fish in the river were dominated by adult chironomids, while most fish residing within the wetland were feeding predominantly on larval and pupal stages (Table 2). This focus of juvenile salmon foraging on wetland benthic invertebrates was coincident with increasing benthic invertebrate taxa richness and density, which was below what might be considered to be the full functional equivalency. However, rigorous evaluation of the status of restored juvenile salmon habitat in Gog-Le-Hi-Te is constrained by the lack of a comparable reference site within the Puyallup River estuary.

While structural attributes are not extremely variable in the short-term, invertebrate prey assemblages can be quite variable on multiple time and space scales and may require extensive sampling to quantify. It is probable that if nearby reference sites having closely similar environmental conditions are available, sampling intensity may be decreased. We do have several examples of appropriate reference sites with prey resource and juvenile salmon foraging data for our studies at Terminal 105 (T105) in the Duwamish River estuary and at Spencer Island in the Snohomish River estuary (Table 1). Juvenile chum and chinook salmon occupying T105 in April 1996 fed predominantly on *Corophium* spp. and *Eogammarus confervicolus* amphipods and on insects (including chironomids), comparable in many respects to the diet of fish caught elsewhere in the estuary (Fig. 2). Benthic invertebrate composition at T105 tended to be comparable to an adjacent reference site (Fig. 3; Kellogg Island [KI] reference *Scirpus*), with similar or higher densities of *Corophium* spp. and *E. confervicolus* in the excavated channel (Fig. 4). Similarly, compared with reference sites and another older restoration site, composition of adult insects sampled within the restoration site were not dramatically different from adjacent reference or other restoration sites (Cordell et al., 1997).

At Spencer Island, less than 2 years after initiation of this dike–breach restoration, much of the diet compositions of juvenile chum (Fig. 5a) and coho salmon (Fig. 5b) in channel and mudflat habitats were comprised of prey that probably originated from within the restored wetland; chironomid larvae, pupae and adults, other dipterans, tipulids, coleopterans, *Corophium* spp., and spiders (Araneae) generally predominated over prey that could have also originated from the adjoining slough. Comparison of benthic organisms from within the restoration site and an adjoining reference site indicated that while oligochaetes numerically dominated all sites, chironomid larvae were actually more common (Fig. 6) and more dense (Fig. 8a) in the wooded edge in the restoration site, and equally dense in other habitats. Composition and densities of reference site insects (Figs. 7 and 8b) illustrated generally more diverse, although not necessarily more taxa-rich assemblages than did the reference habitats.

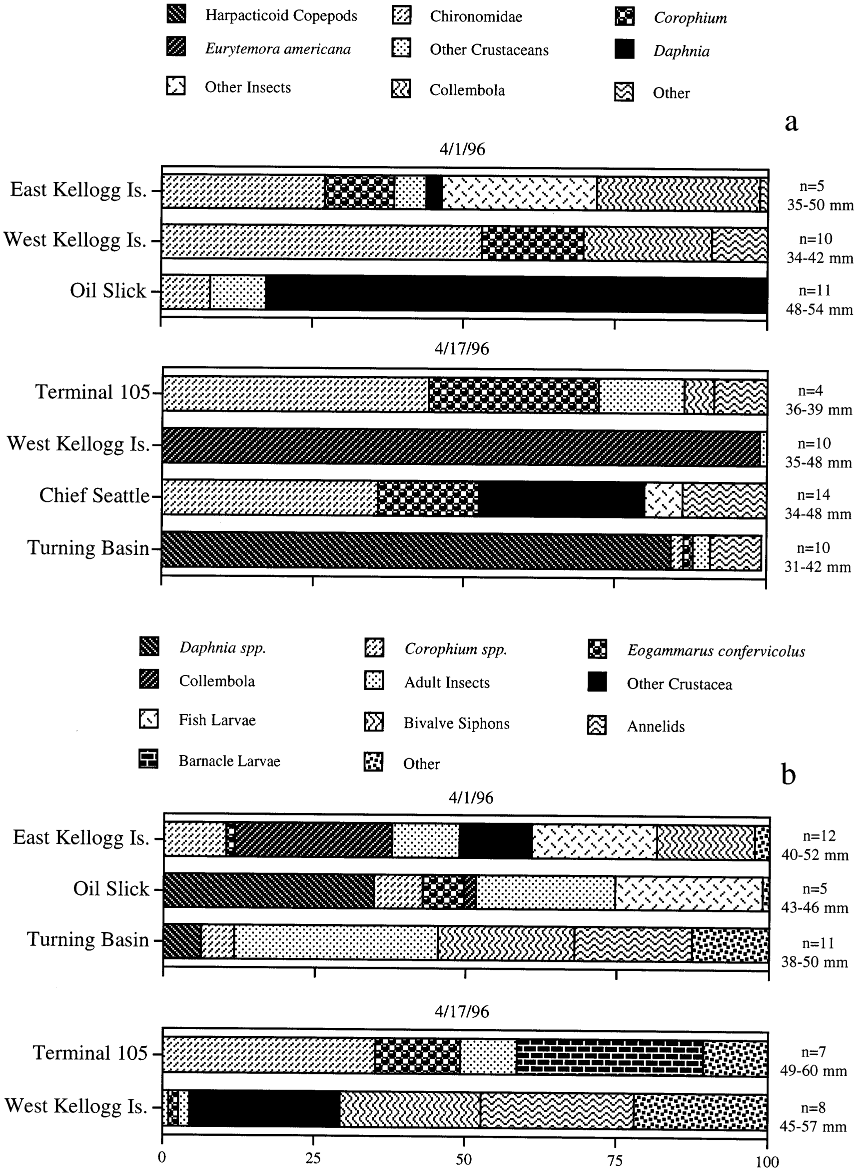

Fig. 2. Prey composition (damped wet wt.%) of juvenile chum (a) and chinook (b) salmon at restoration and reference sites in Duwamish River estuary, Washington in April 1996–May 1996. The most up-estuary sites occur at the top of the graph, the most seaward sites near the bottom. Reproduced from Cordell et al. (1997).

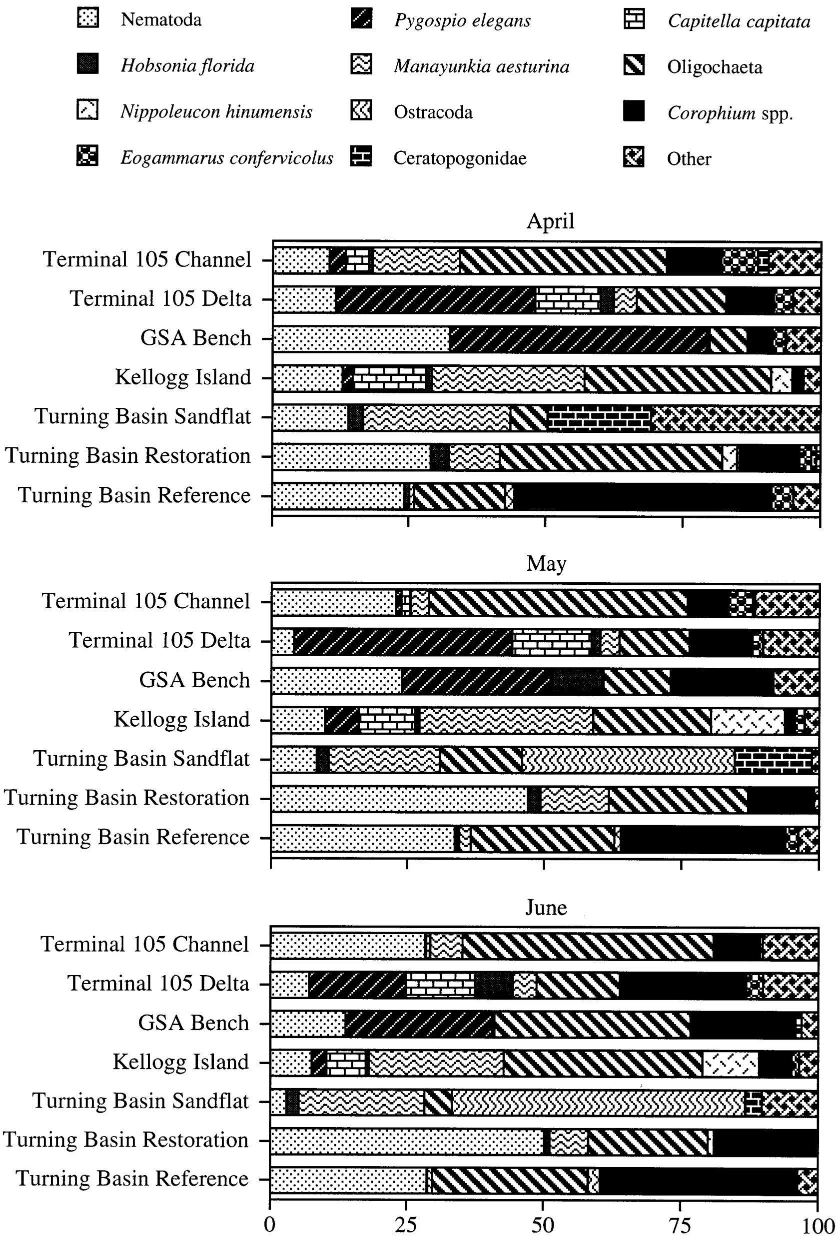

Fig. 3. Numerical composition (percent of total density) of benthic invertebrates sampled by 0.0024 m^2 core in restoration and reference sites in the Duwamish River estuary, Washington in April 1996–June 1996. Reproduced from Cordell et al. (1997).

However, the restoration site had comparable or greater (e.g. mudflat habitat) densities of chironomids. This suggests that recent tidal reflooding of the restoration site has produced extensive detritus from dying freshwater plants and woody vegetation that supports increased chironomid and other detritivore populations on the developing mudflat and marsh surface. We anticipate that this early-intermediate state of capacity for juvenile salmonid foraging will change as the wetland matures more toward an oligohaline marsh similar to the reference sites.

Based on this kind of information, we developed a ‘protocol’ that identified key attributes of estuarine habitats in the Pacific Northwest that promote fish and wildlife functions (Simenstad et al., 1991). The protocol has since been adopted both as a source for useful indicators of the patterns and rates of development of estuarine restoration sites and as a compendium of accepted monitoring methods and data. While we dealt primarily with preferred prey organisms that could serve as assessment criteria for capacity, we were not able to address either structural attributes of particular importance to fish and wildlife or life history requirements of the preferred prey.

Opportunity metrics appraise the capability of juvenile salmon to access and benefit from the habitat’s capacity. We distinguish capability from probability by assuming that probability includes many other aspects associated with the chance of juvenile salmon accessing the habitat, e.g. variability in salmon populations and life histories, the presence and practices of salmon hatcheries, etc. We recognize that, as with all metrics, there is considerable scale of natural variability in opportunity. Explicit metrics and their relationship to opportunity include, (1) tidal elevation, which directly influences the frequency and duration of

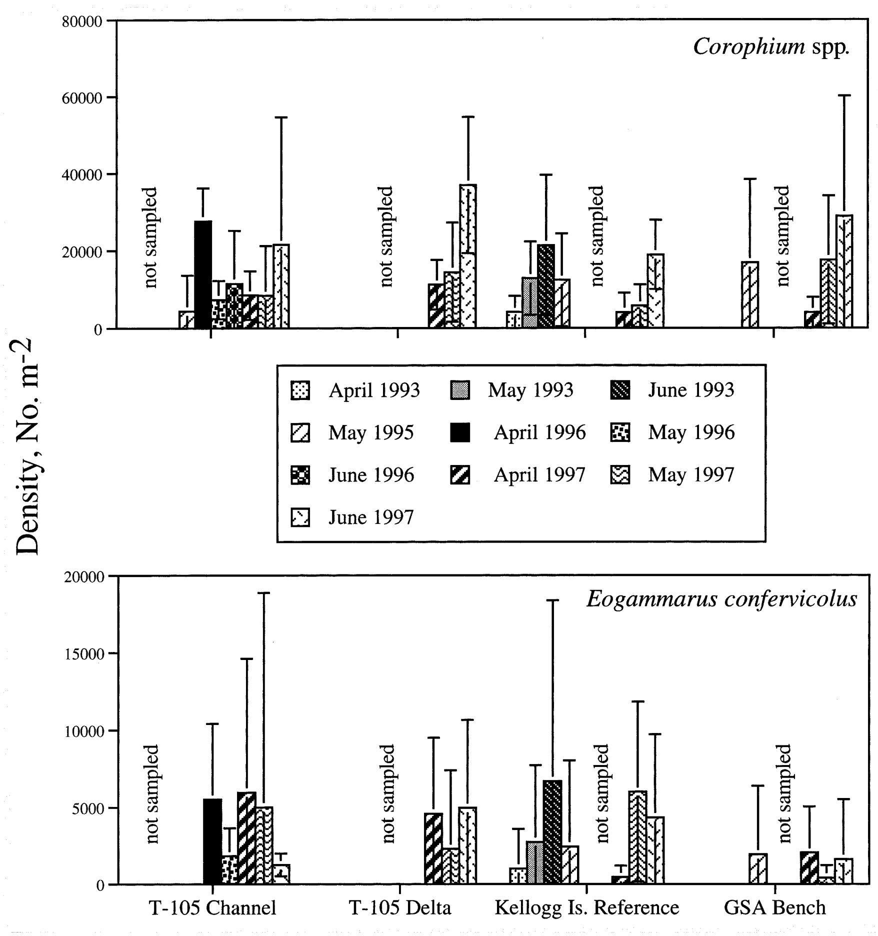

Fig. 4. Densities (vertical lines are 95% confidence intervals) of *Corophium* spp. and *Eogammarus confervicolus* amphipods sampled by 0.0024 m^2 core in restoration and reference sites in the Duwamish River estuary, Washington in April–June 1993–1997.

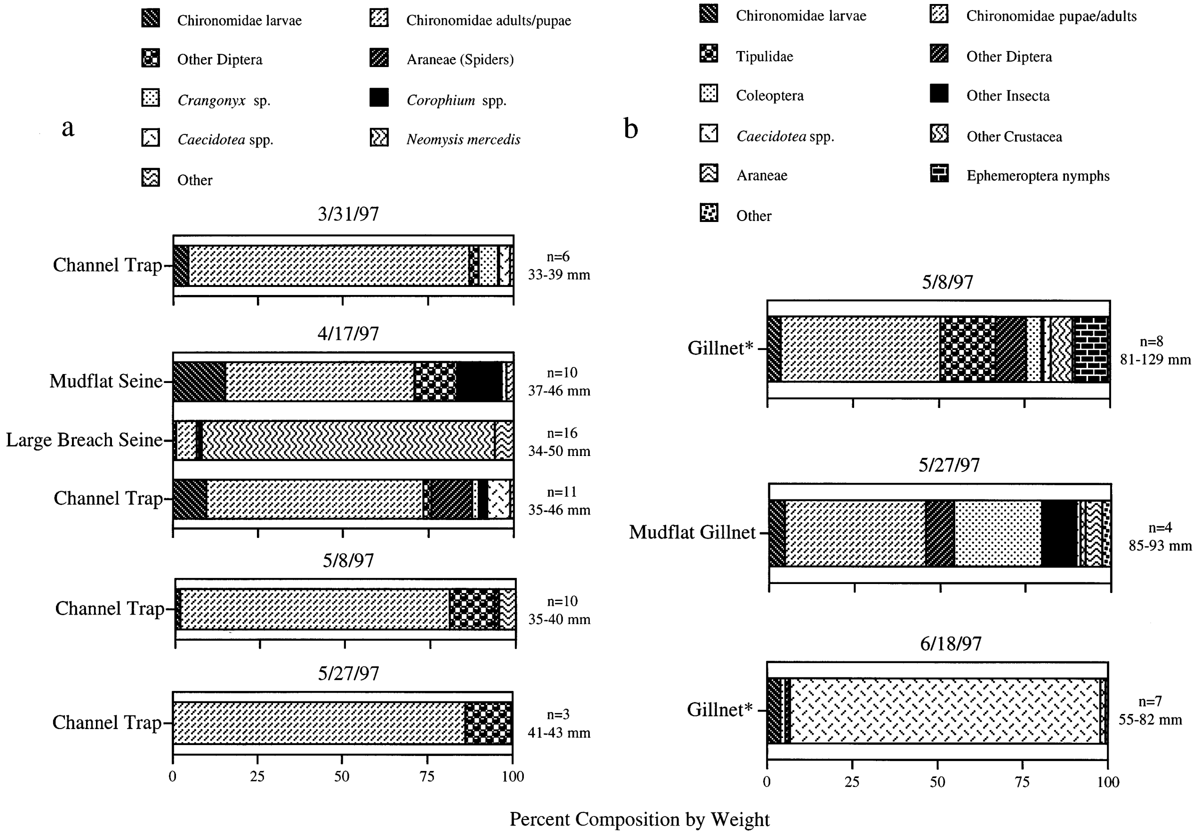

Fig. 5. Prey composition (damped wet wt.%) of juvenile chum (a) and chinook (b) salmon collected by channel trap net, beach seine and gillnet in restored wetland on Spencer Island, Snohomish River estuary, Washington in May–June 1997. Reproduced from Cordell et al. (1998).

tidal flooding; and (2) extent of important geomorphic features, such as total edge and penetration of tidal channels, which often dictate both the extent of fish access into habitats and the interface along which they feed. Other factors are also important, (1) proximity to disturbance (e.g. noise, movement); (2) actual or perceived refugia from predation, such as extent of overhanging vegetation, marsh vegetation height, proximity to deepwater habitats; and (3) the strength of cues that might attract juvenile salmon.

We have been able to measure or infer several opportunity metrics for juvenile salmon. For example, Shreffler et al. (1990) estimated that between 0.06 and 0.6% of juvenile chum and fall chinook salmon, respectively, accessed the Gog-Le-Hi-Te wetland as they migrated down the Puyallup River. There are also two case studies demonstrating that opportunity metrics change over time with the development of restored habitats. During the first 7 years of development of Gog-Le-Hi-Te, extensive sediment accretion and erosion restructured the excavated tidal channels, from a first-order drainage system of broad, deep channels to a fourth-order system of shallow, narrow channels, with significant increases in channel and mudflat or marsh interface (Simenstad and Thom, 1996). The single channel in the Chehalis River created slough (Table 1) has also undergone extensive sediment accretion over 7 years, and fish access at extreme spring low tides has diminished (Simenstad et al., 1997a). However, channel bathymetry, sinuosity, cross-sectional area and *C. lyngbyeii* terraces at this site still differ from the adjacent reference site (Ann's Slough). In this case, accretion and erosion of sediments, colonization by native or exotic vegetation and recruitment of invertebrates have enhanced habitat attributes for fine sediment-dwelling invertebrates that are preferred prey of juvenile salmonids. While opportunity to access the capacity of the system will coincidentally diminish in one respect, as intertidal elevations of mudflats and the marsh plain increase, it will likely increase in another respect, as tidal channel penetration and edge increase (Fig. 1).

Opportunity metrics imply the direct availability of prey at a site. However, opportunity to indirectly exploit a habitat's productive capacity should also be taken into account, because overall estuarine capacity may actually increase coincident with decreasing fish access as a restored habitat matures. Export of both organic detritus and prey resources to adjacent habitats and the estuary's distributary network will increase with the increasing plant community and the drainage

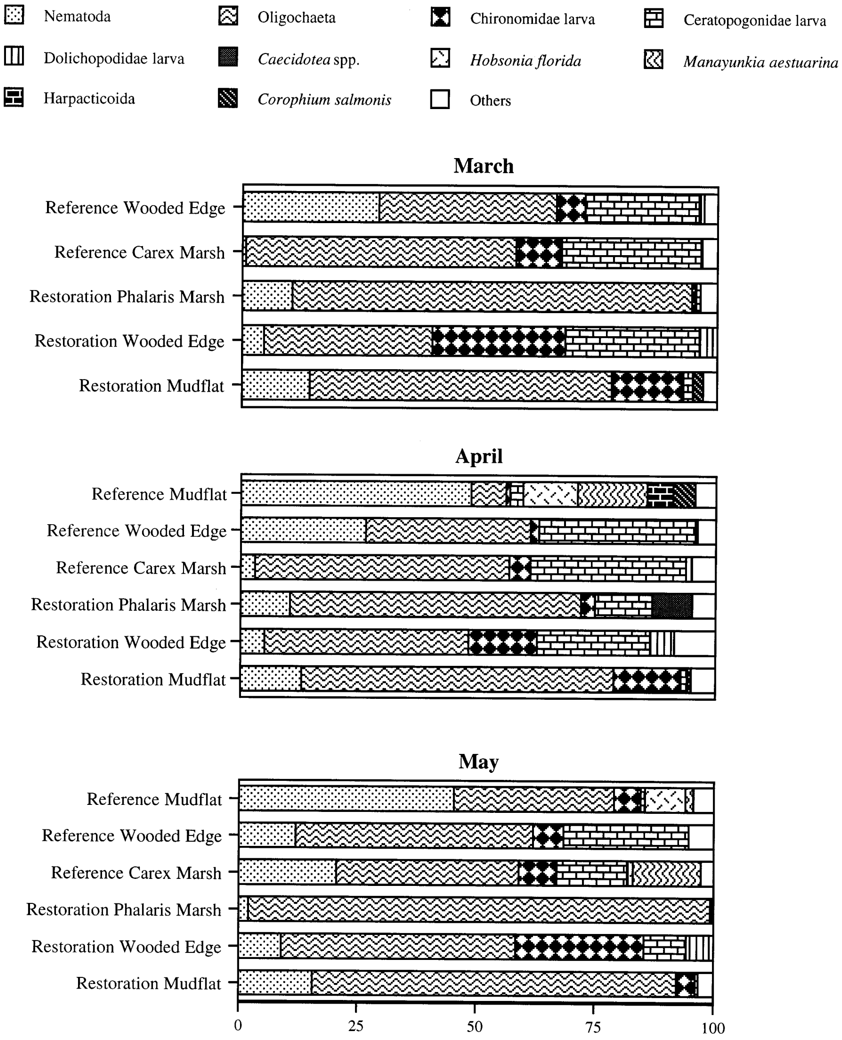

Fig. 6. Composition (percent of total density) of invertebrates sampled by 0.0024 m^2 cores in different habitat strata at restored and reference wetland sites on Spencer Island, Snohomish River estuary, Washington in March–May 1997. Reproduced from Cordell et al. (1998).

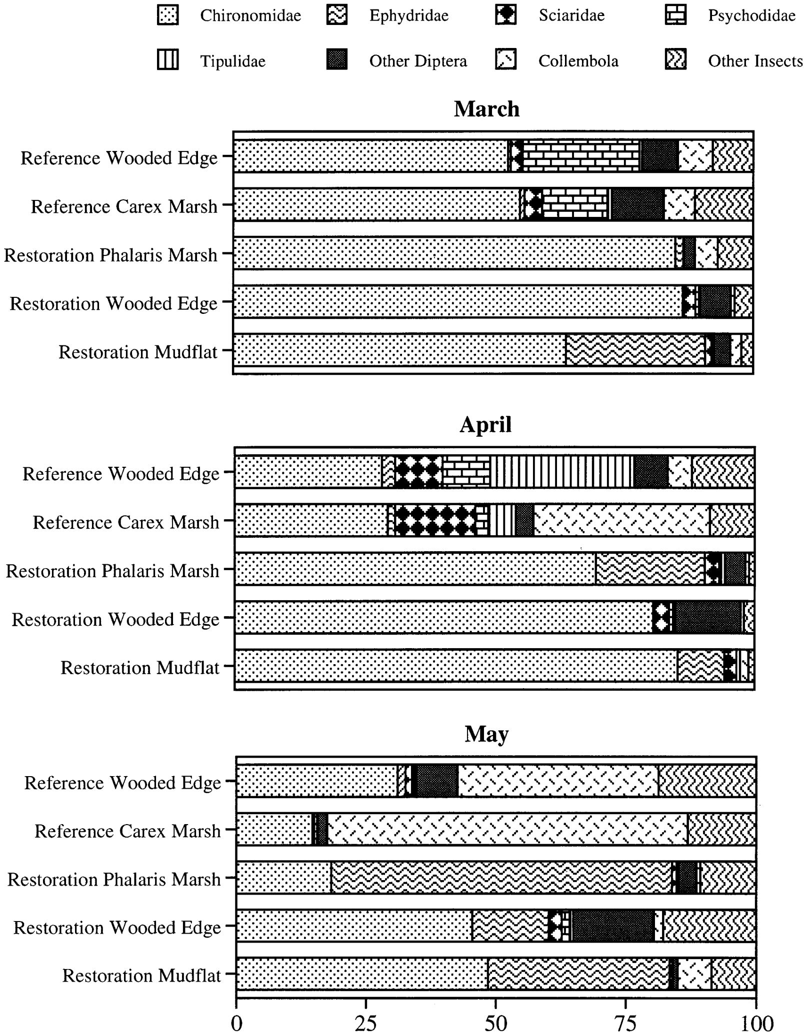

Fig. 7. Composition (percent of total density) of invertebrates sampled by 0.21 m^2 insect fallout traps in different habitat strata at restored and reference wetland sites on Spencer Island, Snohomish River estuary, Washington in March 1997–May 1997. Reproduced from Cordell et al. (1998).

channel development. Autochthonous sources of insects can contribute to drift and neuston concentrations along tidal fronts that juvenile salmon can exploit (Tschaplinski, 1987). Ultimately, the product of *capacity* × *opportunity* would be a most appropriate composite metric of a habitat's overall utility for juvenile salmonids.

Realized function criteria include any direct measures of physiological or behavioral responses that can be attributable to fish occupation of the habitat and that promote fitness and survival. The ultimate metric is a measure of survival, but related metrics includes habitat-specific residence time, foraging success, and growth. Due to the mobility of juvenile salmon, unambiguous measurement of realized function usually requires experimental manipulation to ensure that the habitat in question accounted for the measured variable, a process that introduces its own ensemble of artifacts. In order to validate the relationship between capacity and opportunity metrics and juvenile salmonid survival, it will be necessary to continue to build evidence of the survival or fitness value of habitat attributes at various stages in the maturation of a restored habitat.

Measuring survival directly, even over the short-term, is difficult because mark-and-recapture methods are required in conjunction with reasonable control or documentation of immigration and emigration from the sampling population. Assessing surrogates of survival in a pair-wise comparison to equivalent reference sites is a feasible compromise although demanding more time and effort than measuring capacity and opportunity metrics. Many restored habitats are intertidal and de-water during the extreme (spring) tides in the Pacific Northwest; thus, functional assessment of specific sites can be challenging under many circumstances. The fundamental approach we recommend is 'self-monitoring', letting the fish test whether their occupation of a restored habitat provides residence time, foraging success, or growth equivalent to that achieved in a comparable reference habitat. On average, residence time and growth are reasonable surrogates for survival (also see species-specific chapters in Groot and Margolis, 1991). This does not preclude the importance of other survival factors, such as time of ocean entry, however. While restoration of habitat to promote estuarine rearing will contribute to long-term survival of salmonids, restoration of diverse habitats throughout their freshwater–coastal range is necessary to allow maximal expression of life history traits (Simenstad, 1997).

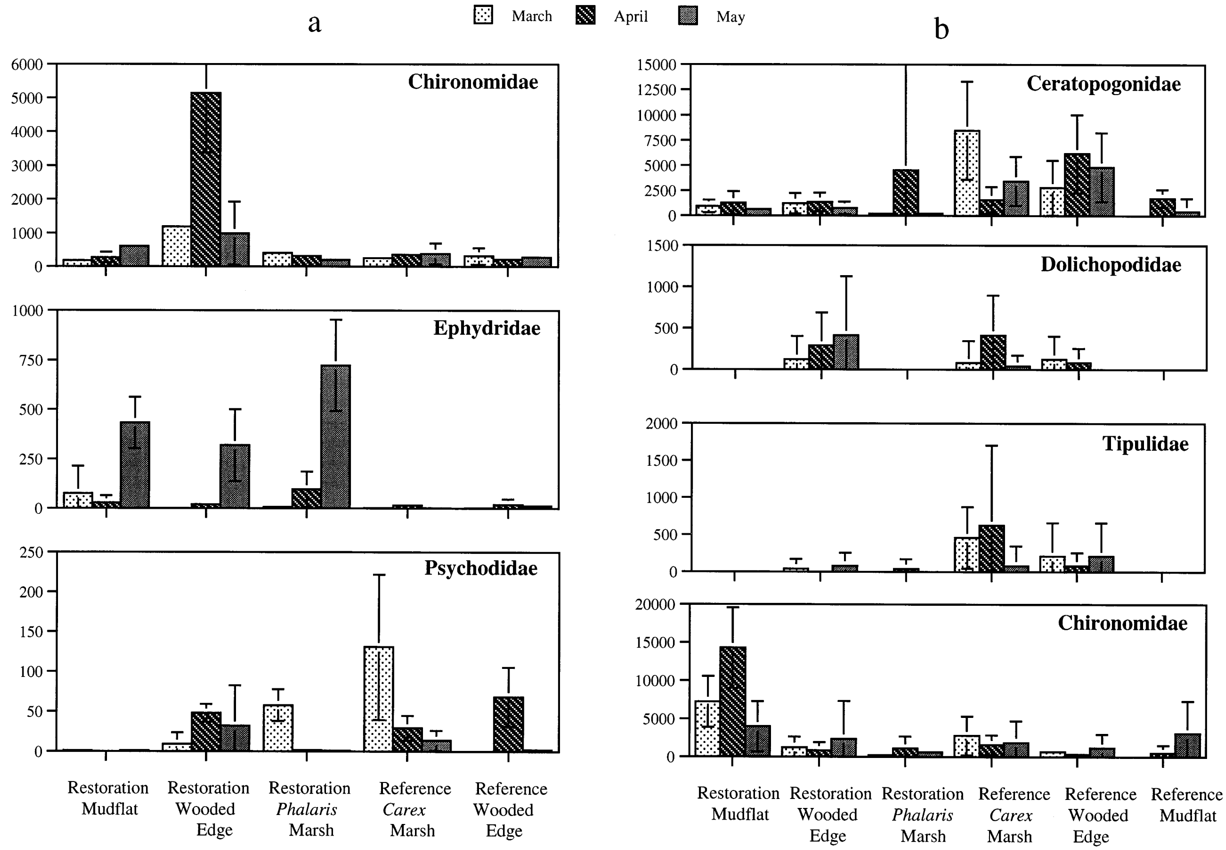

Fig. 8. Mean density (error bars = ± 1 S.D.) of prominent insect larvae sampled by 0.0024 m^2 cores (a) and prominent dipteran flies sampled from 0.21 m^2 fallout traps (b) in different habitat strata at restored and reference wetland sites on Spencer Island, Snohomish River estuary, Washington in March 1997–May 1997. Reproduced from Cordell et al. (1998).

Table 3
Stomach fullness index (instantaneous ration, body wet wt.%) and diet overlap (percent similarity index, PSI) of juvenile chinook and coho salmon in a natural and created slough in brackish reach of the Chehalis River estuary, Washington from Miller and Simenstad (1997)

Site	Date	*n*	Size (mm)	Fullness (%)	PSI (%)
Chinook, *Oncorhynchus tshawytscha*					
Natural	6-20-91	9	41–50	1.4	49.2
Created	6-20-91	11	41–50	1.3	
Natural	6-20-91	17	51–60	1.4[a]	60.6
Created	6-23-91	7	51–60	0.4	
Natural	6-24-92	8	51–60	2.4[a]	58.5
Created	6-24-92	10	51–60	0.8	
Coho, *O. kisutch*					
Natural	6-20-91	5	51–60	1.7	27.3
Created	6-21-91	8	51–60	1.3	
Natural	6-3-92	10	41–50	1.9[a]	57.5
Created	6-4-92	11	41–50	0.6	

[a] Significant Mann–Whitney non-parametric comparison test, $P<0.01$, and $\mathrm{PSI} = 100\text{-}(1/2(\Sigma|X_i - Y_i|))$, where, X_i, percent total IRI for prey category i from the natural slough and Y_i, percent total IRI for prey category i from the created slough.

We have also attempted to assess short-term growth and residence-time responses of juvenile salmon at two restoration sites (Shreffler et al., 1990, 1992; Miller and Simenstad, 1997). Shreffler et al. (1990) found that the residence times for juvenile chum averaged between 1.7 and 2.6 days (range, 1–9 days), and juvenile chinook between 5.1 and 38.3 days (range, 1–43 days) at Gog-Le-Hi-Te. The mean growth rate of the longest resident chinook was estimated to be 0.37 mm per day in length and 5.2 mg per day in biomass. These values are within the natural range of habitat residence times documented for chum and chinook; the chinook growth rate was less than the published mean for morphometric growth but equal to that of somatic growth. We documented that juvenile coho and chinook salmon occupying the created and natural sloughs in the Chehalis River estuary feed on comparable prey taxa, particularly chironomids and aphids, but often with different relative emphasis on specific prey (e.g. coho in the created slough consumed more mysids, and chinook in the created slough more ceratopogonid flies than in the natural slough), such that the similarity in their diet varied between 27.3 and 58.5% (Miller and Simenstad, 1997). Stomach fullness indicated that the fish in the created slough often (three out of five comparisons) had less full stomachs than that in the natural slough (Table 3). However, individual growth trajectories of the juvenile coho, based on daily otolith increment width, did not vary significantly between the created and natural slough over 8–10 days (Miller and Simenstad, 1994, 1997). These results from both restoration sites demonstrate that different metrics may actually be sensitive to different factors in the ability of a habitat to support fish production. Whereas, diet specificity and consumption rate may detect real differences in the availability of preferred prey, individual growth may be a more robust response or factors affecting growth conversion and efficiency may compensate for inherent consumption differences.

4. Salmonid habitats as landscapes

Assessing habitat restoration for anadromous salmonids remains highly conjectural because of at least two gaps in our understanding, (1) whether under the given conditions habitat attributes follow predictable functional equivalency trajectories; and (2) to what degree the support of anadromous salmonids is dependent on landscape, rather than site-specific attributes. Given the longtime frame that many attributes and processes of restored estuarine wetlands appear to require and the state-of-the-science of current analytical approaches, the validity or nature of functional equivalency trajectories may not be resolved in the near future (Simenstad and Thom, 1996; Michener, 1997).

It is becoming evident that goal setting and establishment of criteria for assessing estuarine habitats need to address landscape and system attributes. Applied coastal science has lagged considerably behind terrestrial ecology in assessing large-scale ecological processes that influence the patterns in secondary production. Examples of landscape management applications to estuarine or coastal ecosystems are rare (however, see Irlandi, 1994; Irlandi et al., 1995; Robbins and Bell, 1994; Shreffler and Thom, 1994).

The application of landscape ecology principles to restoration of juvenile salmon habitat is unusually germane (Naveh, 1994; Bell et al., 1997). Landscape processes structure these habitats and influence their function, patterns, and rates of change, and salmon interact dynamically with this changing mosaic of habitats along the entire estuarine gradient. Their response is thus to the organization of patches, corridors, and matrix of habitats through which they move and interact, as a part of the 'trophic relay' to the ocean (Kneib, 1997b).

Examples of potential landscape-scale metrics of estuarine habitat function for anadromous salmonids include, (1) habitat connectivity; (2) continuity between estuarine and undisturbed upland habitat (buffer width and extent); (3) convergences (e.g. number, location) between primary and secondary salinity gradients, e.g. 'side estuaries'; (4) position and orientation of low-energy habitats, such as tidal sloughs; (5) length of uninterrupted (e.g. vegetated) edge or habitat fragmentation; and (6) lengths or network dimensions of entrapment zones (e.g. tidal/current fronts) for neuston and other prey. Of particular landscape interests are the transition points in estuarine migration, such as the freshwater tidal/oligohaline region wherein species and life history stages often must reside for days to weeks to adjust physiologically or seek low-energy habitats during winter storm events. The areal extent and location of low-energy, productive rearing and refugia habitats are likely to be exceedingly important in buffering the stresses of this abrupt floodplain–estuary transition. Perhaps the decline of coho and fall chinook populations that often require extended physiological transition has occurred because of the severe reduction in availability of freshwater tidal/oligohaline sloughs and forested swamps that historically blanketed large floodplain estuaries in the Pacific Northwest. Habitat transitions at the estuary–ocean end of the continuum are also relevant, as this involves dramatic shifts in prey and predators and juvenile salmonids' behaviors to capture or avoid them, respectively. Similarly, low-water refugia (subtidal channels and basins) may effectively dictate the total carrying capacity of small coastal estuaries irrespective of the fishes' responses to shallow-water habitat.

5. Summary

Estuarine habitat restoration cannot be the panacea for recovery of depressed anadromous salmonid populations in the Pacific Northwest. Contrary to the latest argument that estuaries are a major 'bottleneck' to salmon recovery, the compounding of anthropogenic impacts on to habitat, life history, and genetic composition and the inherent natural variability throughout their life cycle indicate a much more complex problem. If restoration of estuarine habitats can contribute to conservation and recovery of compromised salmonid populations, it is imperative that we employ assessment criteria that are ecologically sound, adaptive, and predictive. However, to be effective, restoration goals and assessment criteria must serve the diversity of anadromous salmonid species and life histories that exploit the continuum of estuarine habitats. Habitat managers and restoration scientists must recognize that certain fundamental information is meager or missing in our understanding of restoration of anadromous salmonid habitat, (1) models of processes, patterns, and rates of restored habitat development that directly relate to habitats' functions to enhance salmonid survival; (2) metrics that assess attributes related to habitats' function as physiological and predation refugia; and (3) landscape metrics that take into account that anadromous salmon are integrators of dynamic habitat mosaics rather than individual sites. The ultimate contribution of coastal habitat restoration to the recovery of anadromous salmonid population and life history diversity is in doubt until all phases of restoration — plan, design, implementation, and assessment — are largely based on the ecosystem processes, landscape scales, and success criteria that take into account the dynamics and unpredictable nature of estuarine habitats.

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