Application of Landscape Allometry to Restoration of Tidal Channels

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Abstract

Oligohaline tidal channels (sloughs) in the Pacific Northwest were shown to have allometric form with respect to outlet width and depth, channel length, perimeter, and surface area. In contrast, an artificial slough, excavated to mitigate port improvements, did not conform to natural slough allometry, resulting in high retention of allochthonous inputs and sediment accumulation. Additionally, intertidal sedge habitat abundance was related to slough size for smaller sloughs, but larger sloughs did not fit this allometric pattern. This suggests that sedge habitat in large sloughs has been destroyed due to extensive log storage and transportation from the 1890s to the 1970s. Finally, the abundance of salmonid prey of terrestrial origin—aphids and adult flies—in slough surface waters was correlated with slough perimeter and, for aphids, with the amount of intertidal sedge habitat. An allometric perspective on landscape form and function has several implications for habitat restoration and mitigation: (1) Size-related constraints on replication for landscape-scale studies are loosened (e.g., rather than requiring reference sites that are similar in size to experimental sites, analysis of covariance can be used to control size effects); (2) physical processes, such as sedimentation and erosion, affect landscape form, whereas landscape form can affect ecological processes, so design of restoration or mitigation projects should conform to allometric patterns to maximize physical and ecological predictability; (3) landscape allometry may provide insight into undocumented human disturbances; and (4) allometric patterns suggest design goals and criteria for success.

Key words: hydraulic geometry, landscape allometry, scaling, tidal channels, restoration.

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Introduction

Models of landscape geomorphology show that landforms are allometric or fractal (Woldenberg 1966; Bull 1975; Church & Mark 1980; Mandelbrot 1983; Rodriguez-Iturbe & Rinaldo 1997). This suggests that landscape form can be viewed as a system of related rates of change between various geomorphic features of the landscape (Woldenberg 1966), and thus one might expect correlated rates of change between various biological patterns and processes associated with those landscape features. Put another way, the boundaries of ecosystem compartments can be described by allometric models analogous to those used in organismal biology. Process models of material and energy fluxes across these boundaries can be linked to the allometric description of landscape form to create an allometric description of ecosystem processes. In this way, landscape form and ecological pattern and process can be linked on a landscape scale.

The objective of this article is to illustrate the concept of landscape allometry and its application in restoration ecology by comparing an artificial oligohaline tidal channel (slough) to a suite of nearby natural sloughs that dissect the floodplain of the lower Chehalis River, Washington, U.S.A. The artificial slough was excavated by the U.S. Army Corps of Engineers Seattle District (USACESD) in 1990 as mitigation for dredging impacts to salmon habitat. The USACESD chose a single reference slough to evaluate the excavated slough with regard to salmon usage and salmon prey production. An allometric perspective on this comparison provides several insights into important issues for habitat restoration and mitigation, such as project design and assessment, inference of historical conditions, the influence of landscape form on ecosystem function, and replication in large-scale studies.

Study Site Description

A detailed description of the USACE-excavated slough was previously published (Miller & Simenstad 1997). In general, the estuarine sloughs of the lower Chehalis River are found in a relatively undisturbed floodplain that is bordered to the north by the Olympic Mountains and to the south by the Willapa Hills (46°57′30″N, 123°42′30″W). The estuarine reach of the floodplain is generally 2.5 km wide and extends 15 km from the

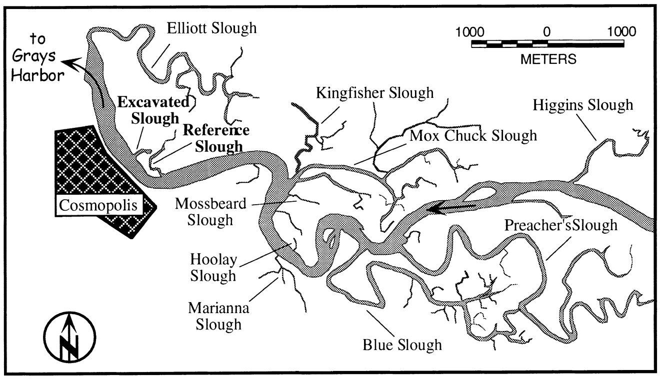

Figure 1. Sloughs of the lower Chehalis River.

downstream cities of Aberdeen and Cosmopolis to diked farmlands upstream (Fig. 1).

The floodplain consists of *Picea sitchensis* (Sitka spruce)-dominated forested freshwater wetlands. Predominant understory vegetation include *Rubus spectabilis* (salmonberry), *Lonicera involucrata* (black twinberry), *Rhamnus purshiana* (cascara), *Cornus stolonifera* (red-osier dogwood), *Salix* spp. (willows), *Carex obnupta* (slough sedge), and *Lysichitum americanum* (skunk cabbage). The floodplain is dissected by sloughs containing two intertidal habitats, mudflats and marsh (Fig. 2). Marsh habitat is usually a monoculture of *Carex lyngbyei* (Lyngby's sedge), growing on a topographic shelf or bench, approximately 0.7 to 1.5 m lower in elevation than the floodplain.

By providing a physiological transition zone, refuge from predation, and source of abundant prey, oligohaline sloughs in the Pacific Northwest are thought to enhance the growth and survival of juvenile salmon (Levy & Northcote 1982; Simenstad et al. 1982; Wissmar & Simenstad 1988). The most important salmonid prey in the Chehalis River sloughs are terrestrial and semi-terrestrial insects, especially aphids (Homoptera), adult chironomids (Diptera), and other adult Diptera. From

Figure 2. Photo of small slough near low tide. Habitat features from the channel outward are inundated channel, intertidal mudflat, intertidal sedges, and forested freshwater floodplain wetland.

April to June, aphids comprise 25% to 90% of the diet for juvenile *Oncorhynchus kisutch* (coho) and from 25% to 70% for *O. tshawytscha* (chinook), whereas adult chironomids may comprise 20% to 50% of the diet for coho and 15% to 55% for chinook (Simenstad et al. 1992, 1993, 1997; Miller & Simenstad 1997).

A thin whitish surface film, pocked with spruce needles and tiny insects, is clearly visible in smaller sloughs but less apparent in large ones. This observation led to the hypothesis that insect prey availability to juvenile salmon varies with slough size. This would be consistent with the hypothesis that slough perimeter and surface area are allometrically related. If allochthonous insect input is a function of perimeter, then insect density (prey availability) would be related to perimeter/area scaling. Additionally, if slough form is allometric, then the amount of intertidal sedge habitat within a slough may also vary with slough size. This is significant for foraging salmon, because the intertidal sedges host large aphid populations.

Methods

Sloughs were chosen for study based on the following criteria: (1) located within the tidal and oligohaline reach of the Chehalis River floodplain, (2) part of a set of sloughs that spanned as large a range of sizes as possible, (3) similar riparian vegetation (i.e., bordered mostly by Sitka spruce), and (4) accessibility (e.g., not obstructed by fallen trees). These sloughs ranged from river-km 0 (Elliott Slough) to river-km 13.7 (Higgins Slough) with most concentrated between river-km 6 and 10 (Fig. 1).

Landform Allometry

To investigate the potential allometry of the Chehalis River sloughs, digitized aerial photos were used of 1:2,400 scale (USACE-SD) to measure slough length, width, perimeter, and surface area. Length was measured along the mainstem of a slough and did not include tributaries. Width was measured at the slough outlet. Perimeter and surface area values included major tributaries to the sloughs. The perimeter was defined as the border between floodplain vegetation and intertidal vegetation or mud.

To determine whether slough geometry varied between slough systems, 1:20,000 scale aerial photos were used (U.S. Department of Agriculture Soil Conservation Service, 1965) to make similar measurements for sloughs of the North River (47°00′N, 123°53′30″W), Willapa River (46°41′00″N, 123°43′30″W), and the South Fork Willapa River (46°41′15″N, 123°43′40″W), which all empty into Willapa Bay. These systems were chosen because each contained a sufficient number and range of sloughs for regression analysis. Additionally, limiting the geographic range to Willapa Bay would make detection of allometric differences between slough systems all the more interesting given an expectation for low geomorphic variation due to presumably similar large-scale geological influences (e.g., tectonic and seismic history, sediment sources, tidal wave modification by the bay). More geographically diverse systems would presumably have greater variation than any found between the Willapa systems.

Slough depth was measured at slough outlets with a plumb line to the nearest 15 cm by taking the deepest of several soundings at a standardized tidal elevation (+2.0 m, determined from tide tables). Depth soundings for all sloughs were made within a 30-minute sampling window spanning high slack tide. The first of the series of sloughs measured was sounded again at the end of the sampling sequence to correct for changes in depth during the ebbing tide.

Channel geometry and intertidal sedge bench formation are both subject to tidal sediment transport processes, so an allometric relationship between sedge bench size and slough size was hypothesized. The extent of intertidal sedge habitat was sampled by measuring the width of sedge benches at 3-m intervals along 100-m transects parallel to the shoreline. Depending on slough size, 5 to 29 such transects were randomly selected for each slough. Sedge bench width was measured perpendicular to the channel with a tape measure to the nearest 0.1 m. Slough channel widths adjacent to the transects were measured from aerial photographs, which were ground truthed for smaller channels. Similar measurements of intertidal sedge habitat width were also made for oligohaline reaches of the Chehalis River. A second approach measured sedge bench width at the slough outlets, a single measurement on each bank. This provided a single standard location for sedge bench width measurements that facilitated comparisons between sloughs. Because the river itself is generally lined by sedges, the measurements for each slough outlet were located inland from the river by a distance equal to the width of the river's sedge bench.

Detrital Insect Outflux

To test the hypothesis that salmonid prey availability varies with slough size, detrital flotsam was collected during May and June of 1993 and 1995 on ebb tides using 0.5-mm mesh nets that resemble oil-spill containment booms. The booms were placed across slough outlets at high slack tide and sampled until low slack tide. Outflux flotsam was skimmed by the booms from the surface of the ebbing water (to a depth of 25 cm), subsampled with a dip net, and sorted through a series of sieves of 13-, 5.6-, and 0.5-mm mesh. Detrital insects were identified to the family level, counted, and weighed (blotted wet weight) to the nearest 0.1 mg.

Statistical Analyses

Dependent and independent variables were log transformed for linear regression analysis to equalize variance in the residuals and to fit power functions, because it was hypothesized that slough form and ecological processes associated with form exhibit scaling analogous to organismal allometry.

Simple linear regression (model 1 regression) assumes that independent variables are not subject to random error or are controlled by the experimenter. When this assumption is violated, alternative forms of regression (model 2) are usually required for unbiased slope estimates. An exception to this requirement occurs when the coefficients of determination (r^2) are very high (>0.9). Under these circumstances, differences between model 1 and model 2 regression are insignificant (Mark & Church 1977). Consequently, traditional simple regression was used in the analysis of the allometry of slough form, even though independent variables were random, because r^2 values were very high.

Analysis of detrital insect flotsam used stepwise multiple linear regression with slough perimeter (log transformed), year of sampling, month of sampling, tidal range during sampling, and sedge width at slough mouth (log transformed) as independent variables and the log transformed wet weight of various insect taxa as dependent variables. Tidal range (high tide minus low tide elevation) was determined from tide tables. StatView 4.5.1 (Abacus Concepts, Inc., Berkeley, CA, U.S.A.) was used for regression analysis. Systat 5.2.1 (Systat, Inc., Evanston, IL, U.S.A.) was used for analysis of covariance and Tukey's HSD post-hoc tests. All tests were conducted at a 5% significance level.

Results

Slough Allometry

Width, depth, and area of all natural sloughs were positively correlated with slough length ($n = 14$, 11, and 10, respectively; $p < 0.0001$ in every case; Fig. 3), with coefficients of determination (r^2) ranging from 0.95 to 0.98. Slough perimeter and area were strongly correlated, with an r^2 of 0.96 ($n = 10$, $p < 0.0001$). Regression analysis of other combinations of these parameters had similarly high r^2 values and low p values (data not shown).

In contrast, the excavated slough fell well outside the 95% confidence bands of all Chehalis slough regression lines (Fig. 3). The excavated slough was wider, deeper, and had greater surface area than natural sloughs of its length and was actually wider and deeper than most of the longer natural sloughs. Furthermore, when the excavated slough was compared with the nearby slough systems of Willapa Bay, it was similarly anomalous (Fig. 4), falling well outside the 95% confidence bands for all three slough systems.

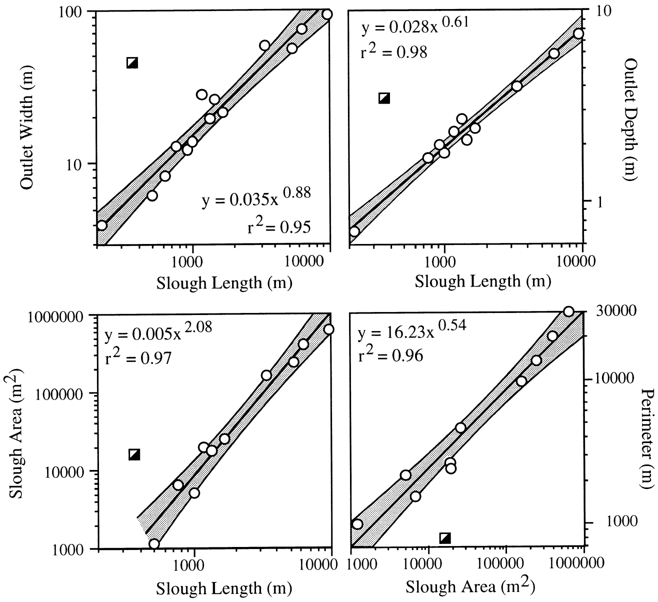

Figure 3. Allometry of slough form for Chehalis River sloughs (○), compared with the excavated slough (◪). Shaded bands are 95% confidence bands.

Analysis of covariance indicated that the morphological scaling of different slough systems varied significantly for width versus length, area versus length, and perimeter versus area ($F_{3,26} = 9.12$, $p < 0.001$; $F_{3,23} = 3.93$, $p < 0.05$; $F_{3,23} = 3.92$, $p < 0.05$; respectively; Table 1). Post-hoc comparisons indicated that width–length scaling of sloughs of the South Fork of the Willapa River differed significantly from those of the mainstem Willapa River and the North River ($p < 0.01$). Likewise, the width–length scaling of the Chehalis River sloughs differed significantly from those of the mainstem Willapa River and the North River ($p < 0.01$ and $p < 0.025$, respectively), whereas there were no significant differences between the South Fork and the Chehalis. Additionally, the South Fork sloughs differed significantly from the mainstem Willapa and Chehalis River sloughs in area–length scaling ($p < 0.05$ and $p < 0.025$, respectively) and perimeter–area scaling ($p < 0.05$ and $p < 0.01$, respectively). There were no other significant differences between slough systems.

Sedge Bench Allometry

Mean channel width and mean sedge bench width for the smaller sloughs and the lower Chehalis River were

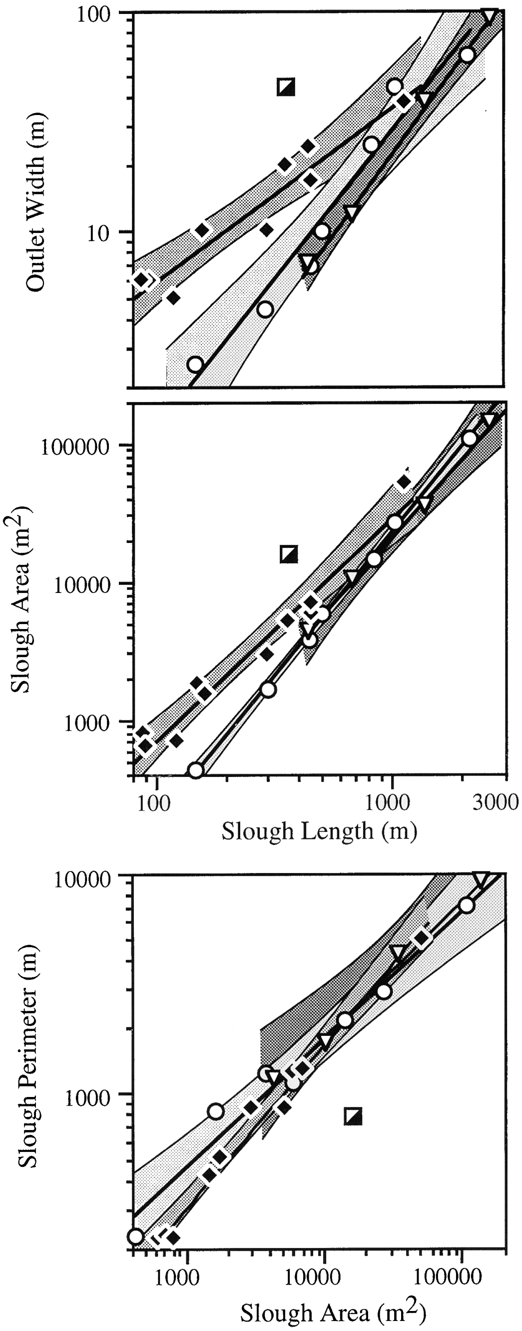

Figure 4. Slough form allometry for the Willapa River (○), South Fork Willapa River (◆), and North River (▽), compared with the excavated slough (◪). Shaded bands are 95% confidence bands.

positively correlated. However, the largest slough, Blue Slough, did not fit this general allometric pattern (Fig. 5A). It had considerably narrower sedge benches than would be predicted by the allometric model—narrower than those in all but the smallest sloughs. Visual inspection of other large sloughs such as Preacher's Slough, Mox Chuck, and Elliott Slough clearly indicated that Blue Slough was representative of large sloughs generally.

Sedge bench widths at the slough outlets showed a similar relationship between slough size and sedge bench width (Fig. 5B). Once again, slough size (outlet width) and sedge bench size (width of sedge bench at outlet) were correlated for smaller sloughs, whereas there was no such relationship for the largest sloughs.

Detrital Insect Export

The most prominent prey in juvenile coho and chinook salmon diets were also the most numerous insects in the outflux flotsam. Aphids comprised 30% of all terrestrial insects in the outflux, followed by adult chironomids (29%) and ceratopogonids (Diptera, 6%). Other adult Diptera (e.g., Sciaridae, Cecidomyiidae, Empididae, Psychodidae, Ephydridae, Tipulidae, and Dolichopodidae) amounted to 7% of the terrestrial insect outflux. Other insect groups were not analyzed because they were less abundant and rarely salmonid prey. Biomass comparisons resulted in a similar ranking: Aphids had the highest biomass (27% of terrestrial insect wet weight) followed by chironomids (16%), other adult Diptera (10%), and ceratopogonids (3%).

Stepwise multiple regression indicated that slough perimeter length (log transformed) was the strongest predictor of exported insect biomass, accounting for 40% to 55% of the variance in the biomass data, depending on the taxon (Table 2). Year of sampling was the second most important predictor, except in the case of aphids. Year explained 13% to 21% of the biomass variance depending on the type of dipteran. Insect abundance was lower in the 1995 collections than in those of 1993.

Sedge bench width at slough outlets (log transformed) was used as an index of sedge habitat abundance, and it was the second strongest predictor of aphid biomass, accounting for 20% of the variance in biomass. Outlet sedge bench width was not a significant predictor for any of the Diptera. Month of sampling during the sampling period was a significant predictor only for ceratopogonids, whereas tidal range was significant only for chironomids. Neither explained more than 7% of the variance in the data. Highly similar results were obtained with insect numerical abundance as the dependent variable and are therefore not shown.

Although detrital insect export increased with slough size (Fig. 6), insect density (biomass/slough surface area) decreased with slough size (Fig. 7). Stepwise multiple regression of the insect density data showed parallel results with those of the previous analysis (Table 3).

The excavated slough did not export flotsam at all. The flotsam nets placed across the outlet of the exca-

Table 1. Slough system comparisons of length (L), width (W), area (A), and perimeter (P) scaling.

Chehalis River	*Willapa River*	*S. Fork Willapa River*	*North River*
$W = 0.035L^{0.88}$	$W = 0.003L^{1.35}$	$W = 0.165L^{0.78}$	$W = 0.001L^{1.47}$
$R^2 = 0.95, n = 14$	$R^2 = 0.95, n = 7$	$R^2 = 0.91, n = 9$	$R^2 = 0.99, n = 4$
$A = 0.005L^{2.08}$	$A = 0.012L^{2.09}$	$A = 0.489L^{1.58}$	$A = 0.034L^{1.93}$
$R^2 = 0.97, n = 7$	$R^2 = 0.99, n = 10$	$R^2 = 0.96, n = 10$	$R^2 = 0.99, n = 4$
$P = 8.24A^{0.54}$	$P = 16.23A^{0.58}$	$P = 1.87A^{0.74}$	$P = 6.52A^{0.61}$
$R^2 = 0.96, n = 10$	$R^2 = 0.97, n = 7$	$R^2 = 0.98, n = 10$	$R^2 = 0.99, n = 4$

The power function exponents derive from the slopes estimated by linear regression of the log transformed variables, as depicted in Figures 3 and 4.

vated slough consistently bowed into the slough rather than being pushed outward by ebbing currents, as was normal in the natural sloughs. Following this unexpected observation, colored marshmallows were placed at four locations along the length of the excavated slough during ebb tides, a different color at each location. These miniature biodegradable drogues served as a simple and easily observed physical model of insect flotsam movement. On three separate occasions, in absolutely still wind the marshmallows moved further into the slough from where they were originally deployed rather than being exported by the ebbing tide.

Discussion

Relationship to Theory

Allometric scaling of slough form is consistent with models of tidal channel hydraulic geometry, which show that tidal prism is correlated with outlet cross-sectional area, depth, and width (Myrick & Leopold 1963; Hume 1991; Leopold et al. 1993; Zeff 1999). The present study's observations on estuarine slough allometry are a logical extension of tidal channel hydraulic geometry, because tidal prism shapes not only the geometry of the slough outlet but also the geometry of every possible cross-section and thus the geometry of the whole slough. These results are also consistent with similar allometric observations in other geomorphic systems such as hillslopes, cirques, dolines, and rivers (Faulkner 1974; Bull 1975; Kemmerly 1976; Graf 1978; Church & Mark 1980; Olyphant 1981) and with fractal models of landforms (Rodriguez-Iturbe & Rinaldo 1997).

Tidal Channel Morphology

Comparison of the allometry of the Chehalis River sloughs with sloughs of the Willapa River, the South Fork Willapa River, and the North River suggests variations in slough geometry among different river systems. The most striking difference is between Willapa River and South Fork Willapa River sloughs. Although these two systems are joined at their confluence, and thus share tidal influences, they do not share a common scaling of surface area, perimeter, length, or outlet width. Differences in their respective watersheds—such as freshwater discharge, gradient, or soils—likely affect the forces sculpting the sloughs. These allometric differences between slough systems suggest that restoration which seeks to mimic natural slough form should consider the local landscape context for the restoration project.

Restored or excavated sloughs that do not conform to the natural allometric template for local sloughs are unlikely to be morphologically stable. Tidal and riverine sediment transport will remold artificial slough shapes, so that non-conforming sloughs will likely follow an unpredictable trajectory toward a more natural form (Fig. 8). Indeed, within four years of construction, the excavated slough in the Chehalis River system began to start headcutting and show significant sediment accumulation (Simenstad et al. 1997). Recent observations indicate a dramatic decrease in the depth and width of the excavated slough, particularly near its outlet, where river-borne sediments are first deposited.

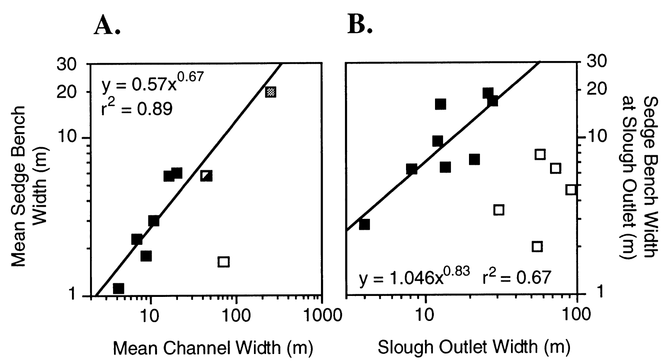

Figure 5. Sedge bench allometry in small sloughs (■) and the lower Chehalis River (▩). Larger sloughs (□) deviate from this allometry. The excavated slough (◪) is shown for comparison. Two measurement methods were used: (A) means of random transects within sloughs and the river and (B) measurements made only at slough outlets.

Table 2. Summary of stepwise regressions.

Dependent Variables	*Slough Perimeter*	*Year of Sampling*	*Month*	*Tidal Range*	*Sedge Width*	$(n)^{R^2}$
log	40%[a]	7%			23%	0.70
Aphid	<0.0005[b]	<0.05	NS	NS	<0.001	
Wet weight	1.14 ± 0.25[c]	−0.26 ± 0.12			1.60±0.41	(24)
log	44%	20%		7%		0.71
Chironomid	<0.0001	<0.005	NS	<0.05	NS	
Wet weight	1.14 ± 0.19	−0.41 ± 0.09		0.08 ± 0.03		(27)
log	55%	21%	6%			0.82
Ceratopogonid	<0.0001	<0.005	<0.05	NS	NS	
Wet weight	1.20 ± 0.18	−0.37 ± 0.10	−0.37 ± 0.14			(22)
log	48%	13%				0.61
Other Diptera	<0.0005	<0.05	NS	NS	NS	
Wet weight	1.04 ± 0.23	−0.32 ± 0.12				(24)

Abundance of allochthonous insects (wet weight, log transformed) is the dependent variable. Length of slough perimeter (log transformed), year and month of sampling, tidal range (high tide minus low tide elevations), and sedge bench width at slough outlets (log transformed) are independent variables. R^2 is the regression coefficient of determination; n = sample size.
[a]Percent of variance explained by the independent variable.
[b]p Value for the independent variable. NS, not significant.
[c]Coefficient for the independent variable ± the standard error of the coefficient.

The likely instability of non-conforming sloughs has several implications for restoration design and planning. For example, the excavated slough in the Chehalis River system was mandated to mitigate dredging impacts to subtidal salmon habitat. Mitigation policy required the excavated slough to contain subtidal habitat. Availability and suitability of property were additional concerns. Consequently, human constraints on design were foremost, and natural (i.e., allometric) constraints were overlooked.

In retrospect, the goal of providing subtidal habitat in such a short slough (i.e., on a small parcel of property) was unrealistic given allometric constraints on slough shape. Subtidal habitat no longer exists in the slough due to sedimentation. Allometric patterns observed in natural sloughs indicate that a slough with persistent

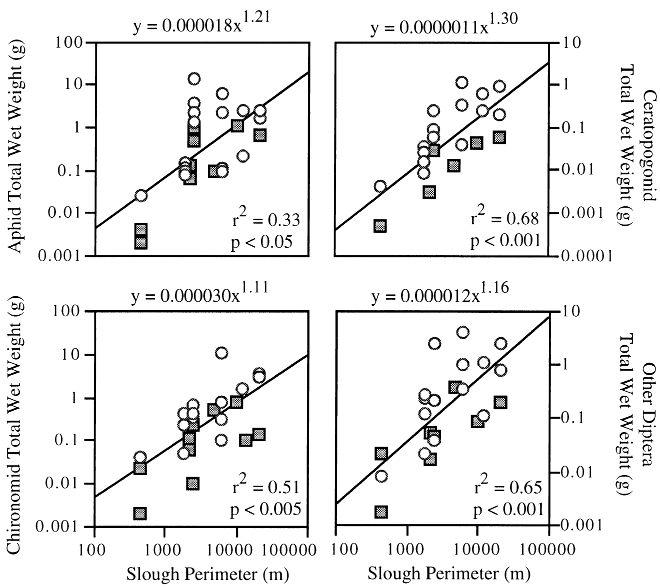

Figure 6. Scaling of detrital insect flotsam export with slough size (perimeter) for 1993 (○) and 1995 (▩).

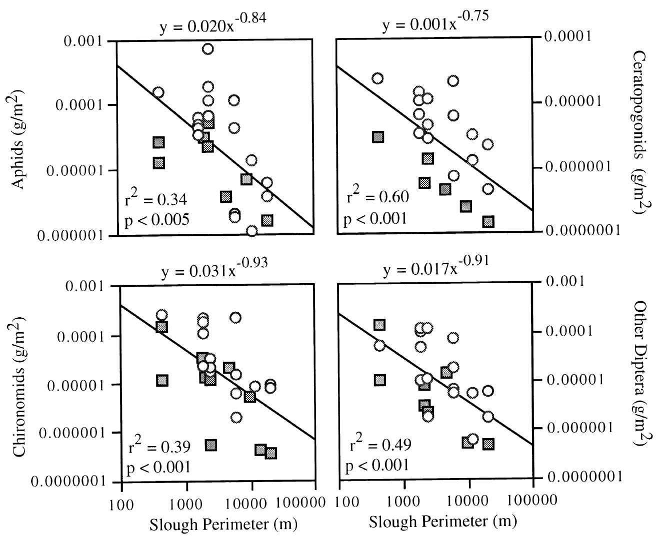

Figure 7. Scaling of detrital insect flotsam density (g wet wt/m² slough surface area) with slough size (perimeter) for 1993 (○) and 1995 (▩).

Table 3. Summary of stepwise regressions.

Dependent Variables	*Slough Perimeter*	*Year of Sampling*	*Month*	*Tidal Range*	*Sedge Width*	$(n)^{R^2}$
	28%[a]	16%			20%	0.64
Aphid	<0.0002[b]	<0.01	NS	NS	<0.005	
Wet wt/area	−0.90 ± 0.20[c]	−0.28 ± 0.10			1.07 ± 0.33	(24)
	34%	22%		8%		0.64
Chironomid	<0.0003	<0.0005	NS	<0.05	NS	
Wet wt/area	−0.90 ± 0.21	−0.42 ± 0.10		0.08 ± 0.04		(27)
	36%	36%	9%			0.81
Ceratopogonid	<0.0001	<0.0001	<0.01	NS	NS	
Wet wt/area	−0.79 ± 0.16	−0.46 ± 0.07	−0.34 ± 0.11			(22)
	36%	16%				0.52
Other Diptera	<0.0005	<0.05	NS	NS	NS	
Wet wt/area	−1.03 ± 0.24	−0.33 ± 0.12				(24)

Density of allochthonous insects (wet weight/slough surface area, log transformed) is the dependent variable. Length of slough perimeter (log transformed), year and month of sampling, tidal range (high tide minus low tide elevations), and sedge bench width at slough outlets (log transformed) are independent variables. R^2 is the regression coefficient of determination; n = sample size.
[a]Percent of variance explained by the independent variable.
[b] p Value for the independent variable. NS, not significant.
[c] Coefficient for the independent variable ± the standard error of the coefficient.

subtidal habitat would have to be at least 3 km long, that is, eight times longer than the excavated slough. This illustrates that landscape allometry can be used not only for stable mitigation design but also to inform decision makers about realistic goals within design constraints. Additionally, a mitigation design that accounts for landscape allometry and mimics natural landforms provides greater confidence in the predictability and sustainability of the design and its goals.

Sedge Bench Allometry

Because of strong allometric relationships among slough length, perimeter, surface area, outlet depth, and outlet width, a similar allometry for slough sedge bench size was predicted. Except for extremely large sloughs, two different measures of sedge bench allometry agreed with my prediction. Historical human disturbance may explain the absence of wide sedge benches in large sloughs. Aerial photographs of the area by the U.S. Army in 1942 and 1944 and by the U.S. Department of Agriculture-Soil Conservation Service from the 1960s to the 1980s show that large sloughs were used extensively for log transport and storage until 1978. Records on floated or rafted logs in the Chehalis River go back to 1904 and indicate that from 1940 to 1960 a half billion board feet of timber were floated down the river annually (Sedell & Duval 1985). Pilings, which assisted in anchoring log rafts and in guiding their movement, are still present in all the large sloughs. Conversely, log storage was not observed in photos of smaller sloughs, nor are any pilings present there. Sedge benches in larger sloughs may have been destroyed by log storage. Log handling and storage in intertidal areas is known to severely impact emergent vegetation by scouring soils and plants during groundings, decreasing light penetration in the water column by direct shading and by increased turbidity from suspended wood fibers, and smothering vegetation through the deposition of bark and wood debris (Sedell & Duval 1985). After the sedges were killed the soil would have eroded away.

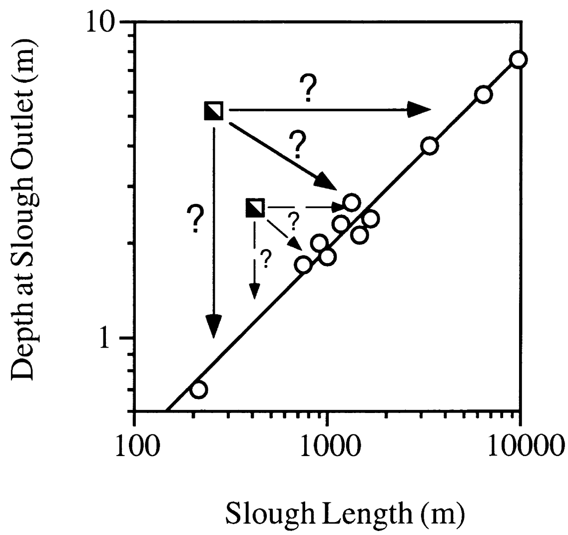

Figure 8. Illustration of potential design uncertainty and instability associated with excavated sloughs (◪) that deviate to varying degrees from the allometry of natural Chehalis River sloughs (○). Larger question marks and longer arrows represent greater uncertainty for the future trajectory of the unstable slough form.

Evidence supporting this hypothesis is still visible in Blue Slough. Many narrow sedge benches in Blue Slough are bordered on each side or further into the channel by lower elevation benches vegetated by *Eleocharis* sp.(spikerush) instead of sedges. These *Eleocharis* benches are not found in smaller sloughs or along the Chehalis River. Thus, larger sloughs appear to contain narrow remnant sedge benches and the eroded remains of sedge benches that have been colonized by *Eleocharis*. This example suggests that landscape allometry can provide insight into historical conditions, assist historical reconstruction of altered sloughs, and thereby contribute design criteria for habitat restoration.

Detrital Insect Flotsam Export

Only aphid export was correlated with sedge bench widths due to their greater dependence on this habitat combined with their lower mobility relative to chironomids, ceratopogonids, and other Diptera, which rear in mudflats and floodplain wetlands and among intertidal sedges (Simenstad et al. 1997). The absence of any effect of sedge bench width on dipteran export suggests that although there is considerable production of dipterans in the intertidal sedge habitat, other sources of dipterans contribute significantly to insect tidal outflux. Another line of reasoning supports this inference. Approximately 16% of insects caught in emergence traps placed among intertidal sedges are adult chironomids (Simenstad et al. 1993, 1997). If intertidal sedges were the predominant source of chironomids in the slough outflux, then the expected proportion of chironomids in the outflux flotsam would be approximately equal to or less than 16%. Instead, 29% of the terrestrial insect outflux were adult chironomids. This suggests that many chironomids are coming from another source, probably the adjacent floodplain wetlands.

Because of its non-conforming shape, the excavated slough does not export detrital insects on ebb tides. Instead, it is a detrital flotsam trap, which suggests that detrital prey items might be of higher density in the excavated slough than in a natural slough of similar size—as measured by width. However, a natural slough of comparable surface area would be half as wide and have a higher perimeter-to-area ratio, so there would be less difference in detrital prey density between the excavated and reference slough. Ann's slough (Fig. 1) was chosen as a reference site by the USACE-SD to evaluate the mitigation slough. The reference slough is 33% less wide, 33% less deep, and has 20% more surface area than the excavated slough. Salmon diets in the two sloughs have been shown to be comparable, but stomach fullness was greater in the reference slough than in the excavated one (Miller & Simenstad 1997). This may have been due to differences in perimeter-to-area ratios affecting insect flotsam density or to the inhibitory effect of piscine predators that were more common in the deeper excavated slough (Miller & Simenstad 1997). Unfortunately, sampling for detrital insect flotsam in the excavated slough was problematic so direct comparisons of flotsam density could not be made.

Reference Sites and Replication

These comparisons raise an interesting question. What is the appropriate reference slough for the excavated slough, one of similar width, depth, or surface area? Does the excavated slough most resemble a small or large natural slough? A mitigation design consistent with a natural allometric template could avoid this issue. By using slough size as a covariate, all the natural sloughs become appropriate reference sloughs. In this way, an allometric approach to landscape ecology reduces the constraints on choosing replicate reference sites.

Caveats

Some biological patterns may not correlate strongly with landscape geometry. Salmonid abundance may not scale with slough size because foraging behavior may change instead. Because of higher detrital insect density, fish might preferentially forage in smaller sloughs, in the smaller segments of large sloughs, or if in larger sloughs they may more actively seek out favorable microhabitats such as eddies behind fallen logs or along shoreline irregularities where insect flotsam might accumulate. Other biotic interactions (e.g., competition, predation, disease, and social behaviors) may also affect fish abundance patterns. Relative to the geometric and physical foundation for ecological patterns, these biological interactions are emergent system properties.

Summary

Mitigation and restoration projects in estuarine slough systems, and probably in other systems as well, should emulate the natural landforms in which the project will be located when mimicry of natural ecosystem function is a project goal. Tidal prism, river discharge, and other factors affecting sediment transport sculpt allometric slough forms. This results in an allometry of intertidal sedge habitat that interacts with slough geometry to affect the density of allochthonous insect flotsam. This in turn may potentially affect the distribution or behavior of fish that feed on the insects. Thus, restored or created sloughs should conform to the natural allometric template of the local system to maximize the probability of mimicking natural slough processes.

Approaching mitigation and restoration planning from the perspective of landscape allometry allows greater confidence in design predictability in a dynamic environment and thus greater confidence in meeting sustainable design goals. A landscape allometry approach to restoration and mitigation planning can also assist in reconstructing historical conditions, thereby providing design goals or criteria for project success. Once the project is completed, replication of reference sites is facilitated because system size can be controlled statistically as a covariate.

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