Carbon content in Oregon tidal wetland soils

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Abstract

This study tested the hypothesis that there is a difference in the soil carbon content of diked, drained and grazed former tidal wetlands, compared to least-disturbed tidal marshes. Soil carbon in tidal wetlands can affect soil ecology, influence wetland functions such as nutrient processing and foodweb support, and serve as an indicator of potential carbon sequestration functions. To provide an initial baseline of soil carbon content of Oregon tidal wetland soils, this study quantified organic matter stored in the top 30 cm of soil in a range of tidal wetland sites along the Oregon coast. Sampling occurred in two sites that had been converted to agricultural production; five sites that had been previously diked, drained and grazed but had undergone hydrologic restoration; and ten least-disturbed reference sites. In this report, these groups are referred to as "unrestored," "restored," and "reference," respectively. The average concentration of soil organic carbon in reference site soils was 15.7%, compared to 12.05% in all disturbed sites (restored and unrestored sites combined) -- a significant difference of 3.7% ± 3.2%. A significant difference was also found between the percent of soil carbon in reference *versus* unrestored sites (15.71% and 9.43%, respectively). These results suggest that restoring tidal hydrology to previously drained sites can increase soil carbon storage and associated ecological functions.

Introduction and Background

This study illuminates relationships between soil organic matter, tidal wetland conversion to agricultural uses, and subsequent restoration. Tidal wetlands provide rich opportunities for research because of their high productivity, their dynamic ecosystems, and their geographic setting in estuaries, which are landscapes of high ecological and social importance. Soil organic matter can affect hydraulic conductivity, soil biota, and aboveground plant communities in tidal wetlands and has recently been highlighted as a valuable research area for carbon sequestration inquiries, especially in tidal wetlands (Gray 2009, Bezemer 2005**,** Laffoley and Grimsditch 2009, Chmura *et al.* 2003).

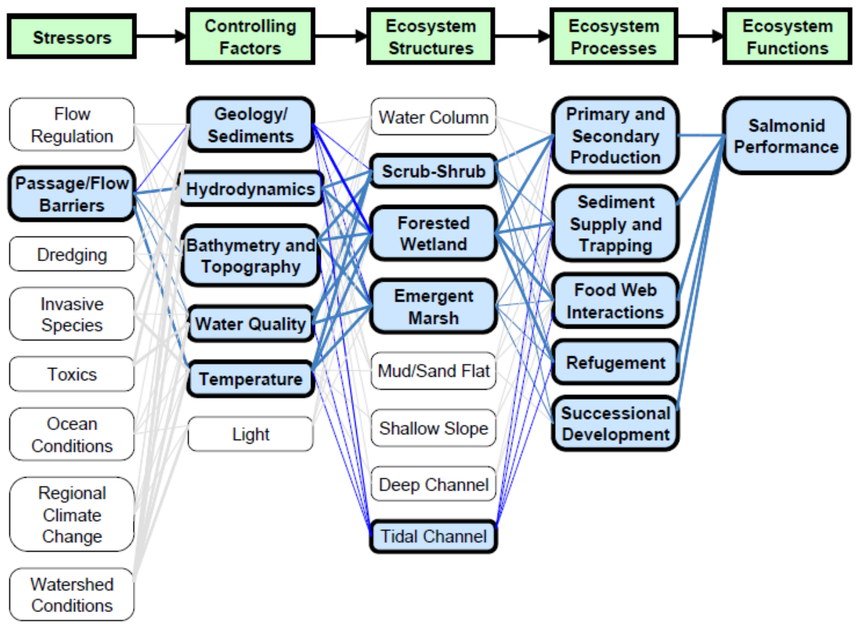

Figure 1. *Tidal wetland ecosystem conceptual model (from Roegner et al. 2008)*

In Oregon, nearly 70% of historic tidal wetlands have been converted to agricultural uses (Good 2000, Christy 2004). Losses of scrub-shrub and forested tidal wetlands ("tidal swamps") have been much higher, as documented in basin-scale studies (Brophy 2005a, Graves *et al*. 1995). Diking, ditching, drainage and livestock grazing are common land management practices, and can result in a comprehensive change in aboveground plant communities (Roman *et al*. 1984). This process frequently results in subsidence of the soil surface due to oxidation of organic matter and direct compaction by livestock (Frenkel and Morlan 1991, Callaway 2001). A conceptual model of a tidal wetland ecosystem is illustrated above in Figure 1 (from Roegner *et al*. 2008). The model shows how tidal wetland sediment characteristics relate to ecosystem structures such as vegetation type and tidal channel formation, which in turn are closely related to ecosystem processes and functions. Awareness of the critical ecological functions provided by tidal wetlands led to the state of Oregon adopting estuarine restoration and conservation as policy in land use planning Goal 16. Since the establishment of Goal 16 in 1977, tidal wetland restoration has made a significant contribution to Oregon's restoration economy (Good 2000).

Soil organic matter is a particularly significant component of soil ecology (Kennedy and Smith 1995). It has been positively correlated with hydraulic conductivity; higher organic matter results in a soil with low bulk density (extremely low in some tidal wetland cases), which reflects the porosity of the soil matrix (Craft *et al*. 1988). This porosity allows water to pass through the soil profile much more freely than in soils with low organic matter (Mitchell 1993, Judson and Odum 1990). In brackish, tidally influenced soils, this subsurface flow can distribute marine-derived nutrients and salts throughout the site (Judson and Odum 1990). The control exerted by organic matter on soil biota and hydrology can dramatically influence surrounding plant communities and the resulting trophic cascades (Hines *et al.* 2006, Oliver *et al.* 2009, Bezemer *et al.* 2005). Because of these important characteristics, soil organic matter, salinity, and pH have been listed among the highest priority monitoring parameters for tidal wetland restoration projects (Zedler 2001, Simenstad *et al.* 1991).

Soil organic matter, and thus carbon, is also an important factor in climate change mitigation and adaptation. Research has shown that tidal wetlands with higher soil carbon content may be more resilient to sea level rise (Cahoon *et al.* 2006, Cahoon *et al.* 2004, Craft 2007, Nyman *et al.* 2006, Morris *et al.* 2002). Remarkably high levels of soil carbon in some tidal marshes have recently brought these systems to the forefront of carbon sequestration inquiries in the global discussion of climate change mitigation (Laffoley and Grimsditch 2009, Thom *et al.* 2001, Trulio *et al.* 2007, Crooks *et al.* 2009, Chmura *et al.* 2003). Lastly, tidal wetland soils research in the US has been concentrated in the Gulf and Atlantic coasts, where estuarine dynamics and ecological communities are very different from those of the west coast. The research presented here helps to fill a large data gap in the Pacific Northwest.

Figure 2. *Study site map*

Methods

Sampling Design

Eight estuaries from the Columbia River estuary in northern Oregon to the Coquille estuary in southern Oregon (Figure 2) were included in this study. A total of 75 samples were collected from 17 sites in these eight estuaries: 25 from ten reference sites, 28 from five restored sites, and 22 from two unrestored sites (Table 1). Table 5 provides detailed site characteristics.

Previously established study sites including tidal swamp, high marsh, low marsh, and transitional zones were used. To leverage study results, we selected sites that had previously been monitored for other purposes, providing detailed data on site history, vegetation and hydrology. Those details are provided in earlier reports by our project team (Brophy 2009, 2005b, 2004, 2002). Among the sites were several restoration-reference site pairs with similar historic habitat class and landscape setting (Table 5).

***Table 1**. Study sites and estuaries*

REFERENCE	**DISTURBED**	
Reference (n=10)	**Restored** (n=5)	**Unrestored** (n=2)
Bandon Marsh (*Coquille R.*)	Millport South (*Siletz R.*)	Waite Ranch (*Siuslaw R.*)
Blind Slough (*Columbia R.*)	Nestucca East (*Nestucca R.*)	Ni-les'tun (*Coquille R.*)
Coal Creek (*Nehalem R.*)	S59 (*Siuslaw R.*)	
Cox Island (*Siuslaw R.*)	S65 (*Siuslaw R.*)	
Duncan Island (*Siuslaw R.*)	Y27 (*Yaquina R.*)	
Hidden Creek Marsh (*Coos R.*)		
Millport North (*Siletz R.*)		
S63 (*Siuslaw R.*)		
Y13A (*Yaquina R.*)		
Y28 (*Yaquina R.*)		

Samples were collected along pre-existing 100m transects which had been established using a stratified sampling method (Brophy 2002). Because of the strong relationships between tidal marsh plant communities, elevation, hydrology, and topography, we assumed that soil characteristics would also be affected by these conditions, and these stratified transects would therefore be appropriate for soil sampling. Previously-established transect markers (PVC posts) aided in transect location. GPS units were used to validate locations or locate transects in the field when necessary.

Samples were collected from the rooting zone (soil surface to 30 centimeters depth), using a Dutch auger following a standard agricultural soil sampling method (Gardner and Hart 1995). When the sample extended into a horizon that clearly lacked any roots (*e.g.* a gleyed clay horizon with no evidence of root growth), that portion of the sample was excluded. Each soil sample was composed of multiple auger cores which systematically distributed along each transect. Auger cores were bulked into a single sample per transect for delivery to the laboratory. Each bulked sample was placed in a plastic zip-lock bag and stored in refrigeration at 2°C until processing in the lab.

Sample date varied by location; month of sampling ranged from July to January, and samples were collected from 2006 through 2011. The date of sampling for each site is shown in Table 5.

Laboratory Methods

Laboratory analysis was conducted at Oregon State University's Central Analytical Laboratory. Samples were dried, homogenized, and a subsample was extracted for analysis. Before homogenization, large roots were removed from samples. Electrical conductivity and pH were measured, and percent organic matter was measured using loss on ignition (Nelson and Sommers 1996, Craft *et al.* 1991).

Data Analysis

Carbon content was calculated from percent organic matter using a conversion specific to high-organic soils (0.68 × %OM) presented in Kasozi *et al.* (2009). Soil salinity was calculated from conductivity values using an online conversion utility (Chapman 2006). Statistical analyses were performed using R and Statgraphics software. Results are reported at the 95% confidence level.

Data were analyzed using two groupings. Grouping 1 compared reference sites to disturbed sites (the latter consisting of both restored and unrestored sites); these comparisons were made using *t* tests. Welch's *t* test was used to compare means of percent soil carbon content. Salinity and pH were analyzed similarly using the Students *t* test. Welch's *t* test is more appropriate for populations with unequal variance, which appeared to be the case for the soil carbon data. Both *t* tests are appropriate for data with equal variance, which appeared to be the case for the salinity and pH data. Reference, restored, and unrestored sites (Grouping 2) were compared using ANOVA and Fisher's Least Significant Difference test.

Potential sampling bias

Differences in plant root structure can affect soil sampling results. In this study, communities of Cespitose (clump-forming) grasses or other dense vegetation often occurred adjacent to areas of exposed soil at sampling sites and presented potential for sampling bias. An effort was made to distribute samples representatively in these conditions. Also, soils associated with certain vegetation types occasionally yielded smaller samples. For example, when drilling the auger into well-established stands of slough sedge (*Carex obnupta*), which have thick and dense root systems, some soil can be pushed out from the sample as roots are cut with the auger blades. Lastly, when sampling in extremely porous soil (as inside a cespitose grass) the high porosity led to a small sample size. In any case, if the auger was less than 2/3 full, the sample was repeated. Otherwise, no effort was made to correct for these circumstances, to maintain a consistent protocol. Since samples with higher bulk density or fewer large roots had the potential to yield more actual mass, these soils could be overrepresented in the bulked sample.

Results and Discussion

All data are presented in Table 4 below.

Soil Carbon

The average concentration of soil organic carbon in reference sites was 15.7% -- significantly higher than at disturbed sites, which averaged 12.1% C (a difference of 3.67% ± 3.20%, $p<0.01$) (Table 2). This result supports the hypothesis stated above, indicating that there is a difference in the soil carbon content of diked, drained and grazed former tidal wetlands, compared to least-disturbed tidal marshes.

Mean carbon concentration at reference, restored, and unrestored sites was 15.7, 13.1 and 9.4% respectively; means were significantly different at the 95% confidence level ($p=0.03$) (Table 3). Pairwise comparisons were made using Fisher's least significant difference (LSD) procedure, and showed a significant difference between the reference and unrestored sites (Table 3). There was no significant difference between restored sites and either reference or unrestored sites.

The lower carbon content at unrestored sites compared to reference sites strongly suggests that drainage and agricultural use of these former tidal wetlands caused loss of stored soil carbon. Worldwide, wetland drainage is associated with large releases of carbon to the atmosphere, a phenomenon of global importance in the face of rising atmospheric carbon and resultant climate change (Armentano 1980). Frenkel and Morlan (1991) measured 35cm of subsidence at a diked tidal wetland in the Salmon River estuary of Oregon. At South Slough National Estuarine Research Reserve, the pre-restoration soil surface elevation at the diked, drained Kunz Marsh site was about 1m lower than the adjacent reference site (Cornu and Sadro, 2002). In both cases, the authors attributed the subsidence at the diked, drained sites to oxidation of soil organic matter, loss of buoyancy, and compaction by livestock and farm machinery.

Although we saw a significant difference in mean soil carbon between unrestored and reference sites, the sample number was small and further studies are warranted. The higher mean soil carbon in restored sites (compared to unrestored sites) may be due to initially high levels of organic matter (before diking and draining), or to accretion of organic matter since restoration.

Table 2. *Soil characteristics by site condition with pairwise comparison results at p=0.05**

Grouping 1: *Reference vs. Disturbed*

		% carbon			**pH**			**Salinity (PSU)**		
Site type	**n**	**Mean**		**Std error**	**Mean**		**Std error**	**Mean**		**Std error**
Reference	10	15.71	a	0.75	5.17	a	0.17	11.94	a	2.18
Disturbed	7	12.05	b	1.45	5.34	a	0.17	5.66	a	2.05

*Means within a column having a common letter are not significantly different at the 5% level of significance (p=0.05).

Table 3*. Soil characteristics by site condition with pairwise comparison results at p=0.05**

Grouping 2: *Reference, Restored, and Unrestored*

		% carbon			**pH**			**Salinity (PSU)**		
Site type	**n**	**Mean**		**Std error**	**Mean**		**Std error**	**Mean**		**Std error**
Reference	10	15.71	a	0.75	5.17	a	0.17	11.94	a	2.18
Restored	5	13.10	ab	1.57	5.52	a	0.16	7.14	a	2.57
Unrestored	2	9.43	b	3.12	4.90	a	0.30	1.96	a	1.75

*Any two means having a common letter are not significantly different at the 5% level of significance (p=0.05).

Three sample values in the dataset were notable. Transect 1 in the Bandon Marsh reference site yielded 7.9% C, a value that was among the lowest in the data set. Much of this site is a relatively young tidal marsh, accreted within the last 150 years, and a 2005 plant community study suggests the site may still be undergoing rapid accretion (Brophy 2005b). Recent and rapid accretion at this site may relate to the post-settlement changes in sediment regime that have been described in the Coquille watershed (Benner 1992). Accelerated sedimentation in the lower

Coquille estuary could relate to the low carbon content at the Bandon Marsh reference site (Brophy 2005b), as could the site's landscape setting in the relatively high-energy environment of the lower estuary.

Two samples at disturbed sites had particularly high carbon content: Transect 4 (T4) at Waite Ranch, an unrestored site (20.4% C), and Transect P3 at S59, a restored site (23.1% C). The Waite Ranch site also showed the highest within-site variability (6.9 to 20.4% C, n=8). In both cases, these observations may relate to the site's historic vegetation class, geomorphology and elevation range. Both sites were historically tidal swamps. The historic vegetation class of the Waite Ranch site was Pacific crabapple swamp, currently a rare ecosystem on the Oregon coast with few remaining examples. Analysis of soil carbon content at a freshwater (diked) crabapple swamp on Oregon's south coast showed unusually high organic matter (25.0% C) (Brophy 2005b). The historic vegetation class of site S59 was Sitka spruce. Studies of soil carbon at least-disturbed willow and Sitka spruce tidal swamps on Oregon's outer coast have shown high organic matter content (12.7 to 26.2% C) (Brophy 2009), so there is a high likelihood that S59 and the Waite Ranch had very high soil organic matter content prior to diking and conversion to agriculture.

Soils high in organic matter are likely to undergo substantial elevation subsidence after diking and drainage. Based on nearby reference sites, we estimate that the lower portions of Waite Ranch have subsided over 1.5m, and S59 is estimated to have subsided up to 1 meter. The resulting low elevations remain saturated much of the year (Brophy 2011), likely conserving organic matter that would have been oxidized under drier conditions. By contrast, higher parts of the site such as the natural levee (e.g. Waite Ranch T7, which had only 8.5% C) have subsided considerably less, probably due to their geomorphic setting. Alluvial deposition processes on natural levees create higher elevations and coarser soil textures, with corresponding better drainage and lower soil organic matter content.

As mentioned in the introduction, our study sites included several appropriate restoration-reference site pairs. At all of these pairs, the disturbed site had lower soil carbon. However, only one pair (Bandon Marsh reference site compared to the Ni-les'tun restoration site) showed a statistically significant difference. Since we observed a significant difference in soil carbon content between unrestored and reference sites across the entire study, the lack of significance within site pairs may be mainly due to the low number of samples per site.

Soil pH

A comparison of reference, restored, and unrestored sites showed no significant difference between groups (ANOVA and Fisher's LSD, p=0.29). This could be due to the small sample size and high degree of variability between sites.

Across all samples, values of pH varied from 3.2 to 6.2, with no apparent trend between samples collected in disturbed versus reference marshes (Student's *t* test, p=0.49). The low pH values we observed are consistent with the mapped soil series at our sample sites (e.g. Brallier, Brenner, Coquille, Nekoma-Fluvaquents complex). Surface horizons in these series are moderately to strongly acid (Soil Survey Staff).

Salinity

No significant difference in salinity was found between reference, restored, and unrestored sites (ANOVA and Fisher's LSD, p=0.12). Our sites included all salinity zones from marine to freshwater tidal, so these zonal salinity differences most likely overwhelmed the reference versus disturbed comparison. No significant difference was found in soil salinity between disturbed and reference sites (p=0.06). Although statistical significance wasn't met, this test statistic remains suggestive of a difference between the two groups.

Table 4. *Soil characteristics by site*

Site	Number of Samples (n)	Site Condition (Reference = 1, Restored = 2, Unrestored = 3)	Sampling Date	%OM	%C	Salinity (PSU)	pH
Bandon Marsh	4	1	7/22/2010	17.59	11.96	14.7	5.5
Blind Slough	2	1	8/28/2007	24.58	16.71	0.48	5.3
Coal Creek	2	1	8/30/2007	21.57	14.66	8.64	4.8
Cox Island	2	1	8/6/2010	23.68	16.1	14.53	4
Duncan Island	2	1	8/6/2010	19.21	13.06	11.39	5.4
Hidden Creek Marsh	2	1	7/17/2008	26.84	18.25	27.62	5.2
Millport North	5	1	9/22/2010	26.51	18.03	7.69	5.4
S63	2	1	8/14/2007	27.75	18.87	11.71	4.8
Y13A	2	1	12/28/2010	19.67	13.38	9.79	6.1
Y28	2	1	11/7/2010	23.11	16.12	12.8	5.2
Millport South	8	2	9/21/2010	22.27	15.14	14.86	5.5
Nestucca East	5	2	1/19/2010	20.5	13.94	3.56	5.8
Y27	9	2	12/28/2010	15.56	10.58	5.11	5.9
S59	3	2	8/18/2006	25.42	17.28	11.24	5.4
S65	3	2	8/18/2006	12.56	8.54	0.94	5
Waite Ranch	8	3	8/7/2010, 9/22/10	18.45	12.55	0.21	4.6
Ni-les'tun	14	3	7/22/2010	9.28	6.31	3.7	5.2

Table 5. Study Site Characteristics

Colors indicate paired site groups. “X” indicates the attribute is not applicable to the site.

Estuary	**Site name and number***	**Number of transects sampled**	**Site category (Unrest**ored, **Rest**ored or **Ref**erence)	**Impact type**	**Impact began**	**Year of restoration (approx)**	**Restoration activities**	**Pair ID**	**Historic vegetation type**
Coquille	Bandon Marsh	4	Ref	X	X	X	X	1	marsh and open water
Coquille	Ni-les’tun	14	Unrest	Diked, ditched, drained, grazed	> 100 years ago	X	X	1	high marsh
Siuslaw	Cox Island (S11)	2	Ref	X	X	X	X	2	high marsh, swamp on E portion
Siuslaw	S59	3	Rest	Diked, ditched, drained, grazed	before 1939	2001	1996 dike breach and tide gate failure, two dike breaches in 2001	2	swamp
Siuslaw	S63	2	Ref	X	X	X	Diked but breached; never ditched	3	swamp
Siuslaw	S65	3	Rest	Diked, ditched, drained, grazed	before 1939	2007	breached dike, filled ditches, planted with tidal swamp species.	3	swamp
Siuslaw	Duncan Island (S30)	2	Ref	X	X	X	X	4	high marsh
Siuslaw	Waite Ranch (S26)	8	Unrest	Diked, ditched, drained, grazed	before 1909	active	none	4	swamp

Estuary	Site name and number*	Number of transects sampled	Site category (Unrestored, Restored or Reference)	Impact type	Impact began	Year of restoration (approx)	Restoration activities	Pair ID	Historic vegetation type
Siletz	Millport North	5	Ref	X	X	X	X	5	high marsh
Siletz	Millport South	8	Rest	Diked, dammed, partially ditched, drained, grazed	1929	2003	Removed outer and one inner dike, filled borrow ditch, connected historic sloughs, LWD	5	high marsh
Yaquina	Y13A	2	Ref	X	X	X	X	6	marsh
Yaquina	Y27	9	Rest	Diked, ditched, drained, grazed	1930s and 1940s	2002	Dikes breached in 2001, channels excavated, large woody debris placed, seeded, ditches filled	6	swamp and high marsh
Yaquina	Y28	2	Ref	X	X	X	X	6	swamp
Nestucca	Nestucca East (Little Nestucca)	5	Rest	Diked, ditched (berms on some ditches), drained, grazed	before 1939	2007	Created channels, connected channels, built levees to protect highway, added large woody debris		marsh
Nehalem	Coal Creek	2	Ref	X	X	X	X		swamp
Columbia	Blind Slough	2	Ref	X	X	X	X		swamp
Coos	Hidden Creek Marsh	2	Ref	X	X	X	X		marsh

*site numbers refer to whole-estuary studies (Brophy 1999, 2005).

Future research

Carbon stocks can be estimated using bulk density and percent organic matter; these data would contribute to discussions of carbon sequestration and potential for soil carbon credits from tidal wetland restoration activities (Crooks *et al.* 2009). The methods presented here provide preliminary data on carbon content in Oregon tidal wetland soils but cannot quantify carbon stocks without supplemental information on bulk density. Because samples were collected along vegetation monitoring transects, future research into soil bulk density for these sites could be conducted in association with other monitoring activities. Finally, the relatively small amount of field effort necessary for the data collection method presented here could complement rapid assessment protocols (*e.g.* Adamus 2010), if more detailed information on soil carbon is of interest in such assessments.

References

Adamus, P.R., J. Morlan, and K. Verble. 2010. Manual for the Oregon rapid wetland assessment protocol (ORWAP). Version 2.0.2. Oregon Dept. of State Lands, Salem, OR.

Armentano, T.V. 1980. Drainage of Organic Soils as a Factor in the World Carbon Cycle. BioScience 30(12): 825-830.

Benner, PA. 1992. Historical reconstruction of the Coquille River and surrounding landscape. Sections 3.2, 3.3 in: The action plan for Oregon coastal watersheds, estuaries, and ocean waters. Near Coastal Waters National Pilot Project, Environmental Protection Agency, 1988-1991. Portland, Oregon: Conducted by the Oregon Department of Environmental Quality.

Bezemer, T. M., G. B. De Deyn, T. M. Bossinga, N. M. Van Dam, J. A. Harvey, and W. H. Van der Putten. 2005. Soil community composition drives aboveground plant-herbivore-parasitoid interactions. Ecology Letters 8:6.

Brophy, L.S. (Green Point Consulting). 1999. Final Report: Yaquina and Alsea River Basins Estuarine Wetland Site Prioritization Project. Prepared for the MidCoast Watersheds Council, Newport, OR. 50 pp.

Brophy, L.S. (Green Point Consulting). 2002. Siletz Bay NWR and Nestucca Bay NWR Tidal Marsh Restoration and Reference Sites: Baseline Plant Community Monitoring and Mapping. Prepared for the U.S. Fish and Wildlife Service, Oregon Coast National Wildlife Refuge Complex, Newport, OR. 98 pp.

Brophy, L.S. (Green Point Consulting). 2004. Yaquina estuarine restoration project: Final report. Prepared for the MidCoast Watersheds Council, Newport, OR. 99 pp.

Brophy, L.S. (Green Point Consulting). 2005a. Tidal wetland prioritization for the Siuslaw River estuary. Prepared for the Siuslaw Watershed Council, Mapleton, OR. 89 pp.

Brophy, L.S. (Green Point Consulting). 2005b. Baseline monitoring of soils and plant communities, and vegetation mapping: USFWS tidal marsh restoration and reference sites, Bandon Marsh National Wildlife Refuge. Prepared for the U.S. Fish and Wildlife Service, Oregon Coast National Wildlife Refuge Complex, Newport, OR 38 pp.

Brophy, L.S. (Green Point Consulting). 2009. Effectiveness monitoring at tidal wetland restoration and reference sites in the Siuslaw river estuary: A tidal swamp focus. Prepared for Ecotrust, Portland, OR. 125 pp.

Brophy, L.S. (Green Point Consulting). 2010. 2010 Monitoring Report: Tamara Quays Tidal Wetland Restoration. Prepared for Salmon-Drift Creek Watershed Council, Neotsu, Oregon. 44pp.

Brophy, L.S. (Green Point Consulting). 2011. Personal communication (unpublished data).

Cahoon, D.R., P.F. Hensel, T. Spencer, D.J. Reed, K.L. McKee, and N. Saintilan. 2006. Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and process controls. In: Wetlands and Natural Resource Management. Eds. J. T. A. Verhoven, B. Beltman, R. Bobbink, D. F. Whigham. Springer, New York.

Cahoon, D.R., M.A. Ford, and P.F. Hensel. 2004. Ecogeomorphology of Spartina patens-dominated tidal marshes: Soil organic matter accumulation, marsh elevation dynamics, and disturbance. In: S. Fagherazzi, M. Marani, and L.K. Blum. (Eds.) Ecogeomorphology of Tidal Marshes. American Geophysical Union, Coastal and Estuarine Monograph Series, Washington, 266 pp.

Callaway, J.C., G. Sullivan, J.S. Desmond, G.D. Williams, and J.B. Zedler. 2001. Assessment and monitoring. In Zedler, J.B. (Ed.), Handbook for restoring tidal wetlands, CRC Press, Boca Raton, Florida, pp. 271-335.

Chapman, R. 2006. A sea water equation of state calculator. APL ocean remote sensing. [Online]. Johns Hopkins University Applied Physics Laboratory. Accessed February 12, 2011 at http://fermi.jhuapl.edu/denscalc.html.

Chmura, G.L., S.C. Anisfield, D.R. Cahoon, and J.C. Lynch. 2003. Global carbon sequestration in tidal, saline wetland soils. Global Biogeochemical Cycles: 1111, doi:10.1029/2002GB001917.

Christy, J.A. 2004. Estimated Loss of Salt Marsh and Freshwater Wetlands within the Oregon Coastal Coho ESU. Oregon Natural Heritage Information Center, Oregon State University.

Cornu, C.E. and Sadro, S. 2002. Physical and functional responses to experimental marsh surface elevation manipulation in Coos Bay's South Slough. Restoration Ecology 10, 474–486.

Craft, C. 2007. Freshwater input structures soil properties, vertical accretion, and nutrient accumulation of Gerogia and US tidal marshes. Limnological Oceanographer 52:3.

Craft, C.B., E.D. Seneca, and S.W. Broome. 1991. Loss on ignition and Kjeldahl digestion for estimating organic carbon and total nitrogen in estuarine marsh soils: calibration with dry combustion. Estuaries 14: 2.

Craft, C.B., S.W. Broome, and E.D. Seneca. 1988. Nitrogen, phosphorus and organic carbon pools in natural and transplanted marsh soils. Estuaries 11:4.

Crooks, S., M. Orr, and D. Brew. 2009. Greenhouse gas mitigation typology issues paper: Tidal wetlands restoration. Report by PWA and SAIC to the California Climate Action Registry. February 4, 2009.

Frenkel, R.E. and J.C. Morlan. 1991. Can we restore our salt marshes? Lessons from the Salmon River, Oregon. *The Northwest Environmental Journal,* 7:119-135.

Gardner, E. H. and J. Hart. 1995. EC 628: Soil sampling for home gardens and small acreages. Oregon State University Extension Service.

Good, J.W. 2000. Summary and current status of Oregon's estuarine ecosystems. Section 3.3, Estuarine Ecosystems. Oregon Progress Board, Salem.

Graves, J.K, J.A. Christy, P.J. Clinton and P.L. Britz. 1995. Historic habitats of the lower Columbia River. Report to Lower Columbia River Bi-State Water Quality Program, Portland, Oregon. Columbia River Estuary Task Force, Astoria, Oregon. 14 pp + maps and GIS cover.

Gray, A. 2009. CICEET macroinvertebrate sampling status report. Prepared for the Cooperative Institute for Coastal and Estuarine Environmental Technology. Accessed online 2/20/2011 at http://ciceet.unh.edu/progressreports/2009/9_2009/cornu06/appendix_1.pdf. 9 pp.

Hamilton, S.F. 1984. Estuarine Mitigation: The Oregon Process. Oregon Division of State Lands, Salem, Oregon.

Hines, J., J. P. Megonigal, and R. F. Denno. 2006. Nutrient subsidies to belowground microbes impact aboveground food web interactions. Ecology 87:6.

Judson, W.H. and W. E. Odum. 1990. The influence of tidal marshes on upland groundwater discharge to estuaries. Biogeochemistry 10:217-236.

Kasozi, G.N., P. Nkedi-Kizza, and W.G. Harris. 2009. Varied carbon content of organic matter in histosols, spodosols, and carbonatic soils. Soil Science Society of America 73:4.

Kennedy, A.C., and K.L. Smith. 1995. Soil microbial diversity and the sustainability of agricultural soils. Plant and Soil 170.

Laffoley, D.d'A., and Grimsditch, G. (Eds). 2009. The management of carbon sinks. A short summary. IUCN, Gland, Switzerland. 8 pp.

Mitchell, J.K. 1993. *Fundamentals of Soil Behavior.* Wiley, New York.

Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, and D.R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. Ecology 83:2869–2877.

Nelson, D.W. and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In

Sparks, D. L., A.L. Page, P.A. Helmke, R.H. Loeppert, P.N. Soltanpour, M.A. Tabatabai, C.T. Johnston, and M.E. Sumner (Eds.). 1996. Methods of Soil Analysis. Part 3—chemical methods.

Nyman, J.A., R.J. Walters, R.D. Delaune, and W.H. Patrick Jr. 2006. Marsh vertical accretion via vegetative growth. Estuarine, Coastal and Shelf Science 69:370-380.

Oliver, J.S., K.K. Hammerstrom, I.W. Aiello, J.A. Oakden, P.N. Slattery, and S.L. Kim. 2009. Benthic invertebrate communities in the peripheral wetlands of Elkhorn Slough ranging from very restricted to well flushed by tides. Report for Monterey Bay National Marine Sanctuary Integrated Monitoring Network (SIMoN).

Ramsey, F.L. and D.W. Schafer. 2002. *The Statistical Sleuth: a course in methods of data analysis*. 2nd Edition. Duxbury Press, Belmont CA.

Roegner, G.C., H.L. Diefenderfer, A.B. Borde, R.M. Thom, E.M. Dawley, A.H. Whiting, S.A. Zimmerman, and G.E. Johnson. 2008. *Protocols for Monitoring Habitat Restoration Projects in the Lower Columbia River and Estuary.* PNNL-15793. Report by Pacific Northwest National Laboratory, National Marine Fisheries Service, and Columbia River Estuary Study Taskforce submitted to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Roman, C.T., W.A. Niering, and R.S. Warren. 1984. Salt marsh vegetation change in response to tidal restriction. Environmental Management 8:141–150.

Simenstad, C.A., C.D. Tanner, R.M. Thom, and L. Conquest. 1991. Estuarine habitat assessment protocol. UW-FRI-8918:-8919, Fish Res. Inst., University of Washington,Seattle, WA, pp. 191.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. (n.d.) Official Soil Series Descriptions. Accessed March 9, 2011 at http://soils.usda.gov/technical/classification/osd/index.html.

Thom, R.M., S.L. Blanton, D.L. Woodruff, G.D. Williams, and A.B. Borde. 2001. Carbon sinks in nearshore marine vegetated ecosystems. Proceedings of the 1st National Conference on Carbon Sequestration, 14-17 May 2001, National Energy Technology Laboratory, Department of Energy, USA.

Trulio, L., J. Callaway, and S. Crooks. 2007. White paper on carbon sequestration and tidal salt marsh restoration. [White paper]. Accessed February 3, 2009 at http://www.pugetsound.org/programs/ science/reports/carbon.

Zedler, J.B. (Ed.). 2001. Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, Florida.