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Andrew W. Traylor for the degree of Honors Baccalaureate of Science in Environmental Science
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Through Wrack Deposition.

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Marine Nitrogen Subsidies to Terrestrial Systems: Transport Through Wrack Deposition

by

Andrew W. Traylor

A PROJECT

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Honors Baccalaureate of Science in Environmental Science project of Andrew W. Traylor presented on May 27, 2010.

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Andrew W. Traylor, Author

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APPENDIX A

Sub-sample of data points where wrack samples were collected from each site.

Site	Marine % Cover	Asin_Sqrt Trans Marine % Cover	Weight (mg)	Dominant sp.	% Nitrogen for Dominant	Nitrogen Deposited (%N*Weight) mg
CA	1	0.100	580	Macro	1.44	8.38
CA	1	0.100	6060	Phyllo	1.66	100
CA	1	0.100	2540	Ulva	2.95	74.9
CA	5	0.224	450	Fucus	1.57	7.06
CA	5	0.224	12600	Nereo	1.53	192
CA	5	0.224	4440	Phyllo	1.66	73.7
CA	15	0.388	10850	Fucus	1.57	170
CA	15	0.388	13130	Macro	1.44	190
CA	25	0.503	54720	Macro	1.44	790
CA	25	0.503	22930	Nereo	1.53	350
CA	25	0.503	6900	Ulva	2.95	204
CA	25	0.503	9290	Ulva	2.95	274
CA	50	0.724	21700	Ulva	2.95	640
GG	1	0.100	170	Nereo	1.53	2.60
GG	1	0.100	470	Nereo	1.53	7.18
GG	1	0.100	520	Nereo	1.53	7.95
GG	1	0.100	1820	Phyllo	1.66	30.2
GG	1	0.100	510	Phyllo	1.66	8.46
GG	1	0.100	660	Phyllo	1.66	11.0
GG	5	0.224	2810	Nereo	1.53	43.0
GG	5	0.224	4630	Ulva	2.95	137
GG	15	0.388	11200	Macro	1.44	162
GG	15	0.388	14150	Macro	1.44	204
GG	25	0.503	9140	Fucus	1.57	143
GG	25	0.503	49220	Nereo	1.53	752
GG	50	0.724	11030	Phyllo	1.66	183
GG	50	0.724	42240	Phyllo	1.66	701
SS	1	0.100	1380	Macro	1.44	19.9
SS	5	0.224	4200	Fucus	1.57	65.9
SS	5	0.224	5370	Fucus	1.57	84.2
SS	5	0.224	990	Fucus	1.57	15.5
SS	5	0.224	2150	Fucus	1.57	33.7
SS	5	0.224	19220	Fucus	1.57	301
SS	5	0.224	2720	Macro	1.44	39.3
SS	5	0.224	4630	Nereo	1.53	70.8
SS	5	0.224	2720	Phyllo	1.66	45.1
SS	15	0.388	8500	Fucus	1.57	133
SS	15	0.388	4580	Macro	1.44	66.2
SS	15	0.388	3350	Ulva	2.95	98.8
SS	25	0.503	27190	Fucus	1.57	426
SS	25	0.503	17020	Fucus	1.57	267
SS	25	0.503	36360	Macro	1.44	525
SS	25	0.503	59630	Nereo	1.53	911
SS	25	0.503	4260	Phyllo	1.66	70.7
SS	25	0.503	28770	Ulva	2.95	849
SS	50	0.724	63470	Macro	1.44	917
SS	50	0.724	68730	Nereo	1.53	1050
SS	50	0.724	42140	Phyllo	1.66	699

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Marine Nitrogen Subsidies to Terrestrial Systems: Transport Through Wrack Deposition

INTRODUCTION

The need to understand how and in what ways ecosystems are connected is becoming more pressing as we realize that fluctuations in one system directly and indirectly affect other systems. This knowledge is particularly important for conservation and management efforts. Knowledge of these linkages between ecosystems helps conservation efforts be more effective by focusing on influential species and areas and facilitate the connection.

Studies of inter-ecosystem connection begun in 1973 when Bruce Hannon applied the economic “input/output theory” to ecosystems (Jørgensen 2007), and have expanded to many types of ecosystem connectivity. Particularly, the ocean-terrestrial interface has been a subject of interest. Cowen et al. (2000) discussed the influence of terrestrial nutrient inputs from rivers on marine larval dispersal and retention. Link (2002) studied the interaction and overlap of marine and land-based food webs in the Northeast US. Bouchard et al. (2000) investigated the nutrient input from loggerhead sea turtles to beaches where nesting sites were located in Florida. Kenchington (1990) and Palumbi (2003) studied the importance of incorporating terrestrial geographic complexity into marine reserves.

Ecosystems are connected and changes in one ecosystem will affect another. The degree of effect between interconnected ecosystems varies, both spatially and temporally. If terrestrial geography provided a variety of habitat types, the marine reserves benefited in terms of species diversity and abundance (Kenchington 1990; Palumbi 2003). Link (2002) showed that terrestrial food webs are connected to and “dependent” on marine food webs. In these studies the dependency appears to be one-sided, however other studies (Bouchard et al. 2000) show a co-dependency. Bouchard et al. investigated how nutrient input from the eggs of loggerhead sea turtles affected the near-by terrestrial system, and conversely, how turtles were dependent on certain beach types and locations.

A specific point of importance lies with nutrient flow between systems. Polis and Hurd (1996) looked at the flow of allothchonous inputs (a source from outside a system) of carbon and nutrients from productive marine systems to relatively unproductive terrestrial systems. They proposed that the flow of nutrients between two juxtaposed ecosystems was a key feature in the structure of energetics, population dynamics, and food webs. This inter-ecosystem flow of nutrients, and its corresponding effects on the respective flora and fauna, has vast implications on both systems dependencies (a dependency on another ecosystem) and livelihoods. The term “livelihoods” is used here to refer to general ecosystem health as discussed by Hearnshaw et al. (2005). The magnitude, temporal, and spatial variation of this nutrient “sharing” has potential for significant importance when implementing conservation strategies and marine reserves. Understanding the link between oceans and land is even more critical now that Earth’s climate is changing quicker than ever before. Because global climate change may influence hydrogeography, storm patterns, and nutrient delivery, it is important to understand how these coming changes will influence both marine and terrestrial ecosystems.

Statement of Purpose

This thesis, along with several other projects, is part of a larger study investigating nutrient flow from marine to terrestrial systems. Other on-going projects are exploring the upland aspects of this flow, while this study inspected the marine derived source of nutrient flow. The goal of this study was to look at the spatial variability of marine-derived nitrogen inputs in adjacent terrestrial communities. Specifically, the focus was on how nitrogen flows by way of seaweed deposition on beaches (commonly known as and hereafter referred to as “wrack”). This wrack creates a subsidy of nitrogen on the beach that is available to terrestrial systems. Subsidy is used here to refer to a pool of nutrients (in this case nitrogen) that can be or are used by organisms to supplement other sources of nutrients.

Dependent on geography and topography of the respective system, each wrack deposit can contain several types of marine algae and/or seagrass (Orr et al. 2005). This composition holds nitrogen and other nutrients that eventually transfer into the nearby terrestrial systems by way of biotic and abiotic factors. Foraging animals like deer, raccoons, and birds feed on the wrack deposits or on the arthropods that live in the deposition and then defecate in terrestrial areas (Duggins et al. 1989). As well, storms and extreme high tides push deposits into the tree line (Duggins et al. 1989). Although each seaweed species in the wrack accumulation experiences nitrogen degradation to some degree (Norderhaug 2003), it has been shown that these deposits do contribute to nitrogen levels in upland environments and alter soil chemistry (Orr et al. 2005; Feagin and Williams 2008). This study quantified the dominant algae and seagrass species found in wrack deposits and compared their relative contributions to the total nitrogen deposited on a beach with regard to spatial variability.

Objectives

Objective 1: Percent Cover

The study quantified the surface area that wrack deposits covered at each beach. Percent cover variation was investigated within sites and also between sites.

Objective 2: Dominant Species

The study determined the dominant species found in each wrack deposit. Many types of kelp have flotation adaptations, which may lead to average higher depositions when compared to other algae. Therefore, the hypothesis tested was that kelp species would occur as the dominant species at higher elevations most often in wrack deposits.

Objective 3: Nitrogen Contributions

The study determined the nitrogen contributions that each dominant species made to the total nitrogen content on a beach. It has been found that species of kelp generally uptake more nutrients initially compared to other algae (Mumford 2007; Orr et al. 2005). Based on these findings, the study tested the hypothesis that kelp would provide the most nitrogen contributions to each wrack deposit.

METHODOLOGY

Sites

The sites chosen for this project were arranged along the Olympic Peninsula in Northwestern Washington (Figure 1). Each site contained an exposed, rocky intertidal bench and the adjacent stretch of sandy beach. Three of these beaches were chosen as survey sites for this study and the adjacent three rocky benches were also surveyed. An effort was made to find similar sites, in respect to size, aspect, and slope. The beaches accumulated a substantial amount of wrack deposition, most of which is assumed to have originated at or near the adjacent rocky benches surveyed.

Comment [MTK1]: Here is a general paragraph where you speak about the study set up generally. I like how you go into the idiosyncracies of each site- but for form, do that in separate paragraphs.

Comment [AT2]: Good point. Changed the first paragraph to flow better.

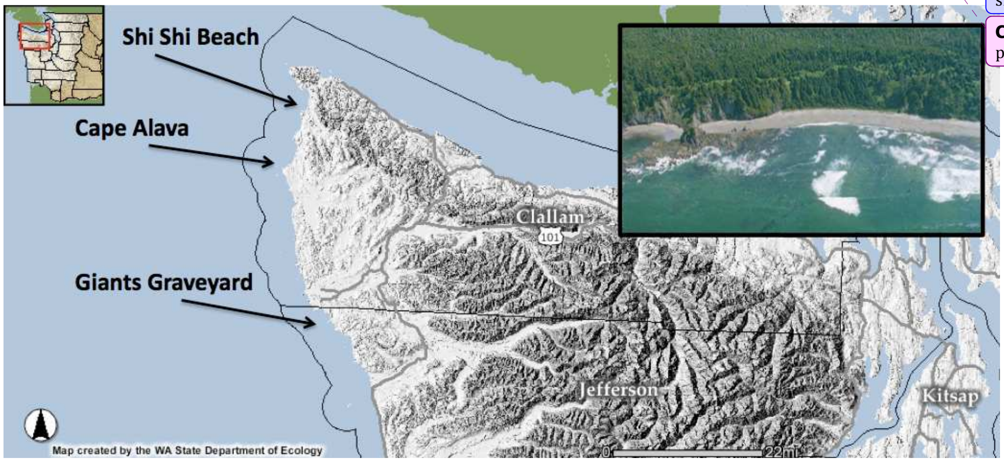

Figure 1. Arrangement of sites on the Olympic Peninsula. Inset shows typical survey site with rocky headland and adjacent sandy beach.

Giant's Graveyard (GG) was the southern-most site (48 14.86, 124 42.08). This site also included the large headland to the north commonly known as "Taylor's Point". The rocky benches found on this headland and the surrounding small, offshore islands are believed to be the source of wrack on the beaches of Giant's Graveyard. Observed strong wave action was present

Comment [AT3]: Up-dated Lat/Long from Waypoint data. Is this the correct way to express this?

on many of the rocky benches at GG, contributing to the exposed nature of the site. Within the larger sandy beach area at GG, three smaller sections of beach were chosen to sample.

Cape Alava (CA) is located approximately 26 miles north of GG (48 10.19, 124 43.96). This site was protected by *Nereocystis* and *Macrocystis* gardens were also found offshore, which dampen wave action. Crashing waves and swells were less pronounced at CA as they were at GG. The adjacent beach to the island was similar to the beaches found at GG and could be classified as a west-facing sandy beach. Three sections of beach within the larger beach area were picked at CA to survey as done with GG.

Comment [MTK4]: By what??? It's relevant because it is protected by a combination of the large island and the kelp forests!

Shi-Shi (SS) was the northern-most site used in the study (48 15.50, 124 41.01). It is located off the tip of the Olympic peninsula, close to Neah Bay. This site was similar to CA and GG in size, species assemblage, and habitat complexity. The exposure on the rocky benches here was moderate, not as protected as CA, but not as harsh as GG. The sandy beaches were similar to the other sites, with three sections of beach chosen to survey as above.

These three sites have been studied over the past two years (2008 and 2009) with the majority of work occurring in the summer months (May through August) with roughly one sampling and survey trip per month.

Survey and Collection Methods

Each site contained three beaches where surveys were taken to determine percent cover of wrack, dominant species in wrack deposit, slope, and aspect. Each beach at a site had five vertical transects located 50m apart that ran perpendicular to the shoreline starting at mean higher high water (MHHW), and moving towards the tree line (Figure 2). At the three sites, mean higher high water was ~8.6 ft above sea level. The distance from MHHW to the tree line varied by site and beach but was typically 30-35m along ground.

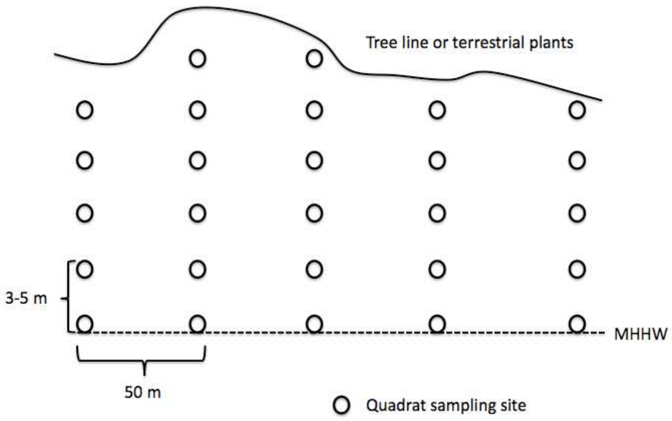

Figure 2. Typical survey site for a beach. Five vertical transects running from mean higher high water (MHHW) up to the tree line.

For each vertical transect, a quadrat survey to estimate percent cover was conducted starting at MHHW and moving up each vertical transect at 3 or 5 meter intervals, depending on beach slope. Since the slope of the beach at each site differed, the corresponding elevational change varied. At GG, a 3 m difference along the vertical transect was equivalent to a 0.212 m elevation change, while at CA it was 0.211 m, and SS, 0.207 m. Surveys continued up the vertical transect until terrestrial vegetation became abundant or the tree line was reached. For each quadrat with percent cover of marine debris, the dominant species of the wrack deposit was recorded. Samples of the wrack deposition from a variety of percent covers were collected and brought back to the lab. At each beach, the slope of each vertical transect was recorded and then averaged for each site. Shi Shi Beach had an average slope of 3.95°, Cape Alava 4.03°, and Giants Graveyard 4.06°.

Comment [AT5]: Now with actual elevations! Does this make sense?

Biomass and Percent Moisture

Samples were collected from the wrack deposits at each beach, stored in liquid nitrogen, and brought back to the lab. Each sample was washed to remove any sand or other non-algal material. Wet weights were obtained, and then the sample was dried using an industrial-sized vegetation drier. Dry weights of the samples were then obtained to estimate biomass by elevation (Figure 5) and percent moisture content (Figure 6) and to determine final biomass.

Carbon to Nitrogen Analysis

From some of the wrack samples, dominant species were identified, separated, weighed and dried. Once dominant species were determined, five samples of that species were set aside for C:N analysis. The samples were pulverized into a fine powder, packaged for combustion, and processed on a Carlo Erba elemental analyzer in a lab at Oregon State University to determine amounts of carbon and nitrogen present in each sample. Protocols were followed for the lab based on methods used to determine elemental ratios as outlined in Hedges and Stern (1984).

Comment [AT6]: Is this better?

Statistics and Calculations

Percent dominance of species was calculated for each site individually. It was found as the percentage of times a certain species was recorded as the dominant species in a wrack deposit. These percentages are shown in Figure 4 and graphed against elevation above MHHW.

Mean percent nitrogen values were found for each dominant species, and a sub-sample data set (Appendix A) was taken from the larger data set of wrack surveys. This smaller data set was representative of average percent covers found at that site. Each of these points in the set represents at place where wrack deposits were collected. For each point a dry weight for the sample was determined and the dominant species in the sample was recorded. A percent nitrogen value was then assigned to each data point representative of the dominant species. Total nitrogen deposited from that sample was then determined as the product of the percent nitrogen of the dominant species and the dry weight of the sample as shown in Appendix A.

The nitrogen deposited in a sample was graphed against the percent cover of that sample as shown in Figure 7. Percent cover was quantified in cover classes (1%, 5%, 15%, 25%, etc) and the data points appear in the figure as grouped in those classes. The percent cover data was arcsine square-root transformed to aid in a normal distribution of the data (Orloci 1966). Figure 7 shows the data fitted with a linear regression and representative R^2 values.

Functions for nitrogen deposited by marine percent cover for each site are given as the regression equations from Figure 7 a), b), and c). With those equations, it was possible to determine the value for total nitrogen deposited at each site once the mean values for percent marine cover were determined. From the entire data set collected in the site surveys, mean values for percent marine cover were determined for each site as shown in Table 3. Cape Alava had the highest value for mean percent cover followed by Giants Graveyard and Shi Shi Beach.

The linear regression equations are in the form of "y = mx +b". The value for mean percent cover represents the "x" variable in this equation.

Shi Shi Beach

Mean % cover (per m^2) = 3.93 Linear regression → $y = 1540x – 285$
$y = 1540(3.93) – 285 =$ **5.77 g N per m^2**

Giants Graveyard

Mean % cover (per m^2) = 9.29 Linear regression → $y = 774x - 65.6$
$y = 774(9.29) - 65.6 =$ **7.12 g N per m^2**

Cape Alava

Mean % cover (per m^2) = 26.5 Linear regression → $y = 925x - 82.5$
$y = 925(26.5) - 82.5 =$ **24.4 g N per m^2**

Thus, by substitution the total nitrogen deposited at each site per meter squared was calculated and are summarized in Table 3.

An ANOVA was performed to test for a significant difference between sites. Once a difference was determined, a Tukey multiple comparison analysis was performed to evaluate the relationship between sites. It was determined that, for total nitrogen deposited, Shi Shi Beach and Giants Graveyard were roughly equivalent while Cape Alava had a significantly higher value for nitrogen (CA> SS~=GG; $F_{2, 881} = 65.8$; $p<0.0001$).

RESULTS

Dominant Species

We quantified seven genera, one complex of macroalgae, and one genera of vascular plants in wrack deposits. Of these, five species were found to be dominant in wrack deposits at all sites. The most common dominant was *Phyllospadix* spp., presenting as the chief species 39% of the time (Figure 3). The second most dominant species was *Fucus gardneri* found dominant 21% of the time, preceded by *Macrocystis integrifolia,* at 14%. *Ulva* spp. and *Nereocystis luetkeana* were both dominant 9% of the time. Although there was variation between sites, these five species proved to be major components of the wrack deposition.

Egregia sp., *Alaria sp.*, and *Laminaria sp.* were found dominant less than 3% of the time during the surveys. Rhodophytes were difficult to identify, especially if specimens were damaged or incomplete, and thus were grouped into the complex of "Reds". Examples of these rhodopytes include but are not limited to *Cryptopleura sp.*, *Microcladia sp.*, *Odonthalia sp.*, and *Endocladia sp*. This complex was also found dominant 3% of the time (Figure 3). Unidentifiable seaweeds were found less than 1% of the time and are not reported.

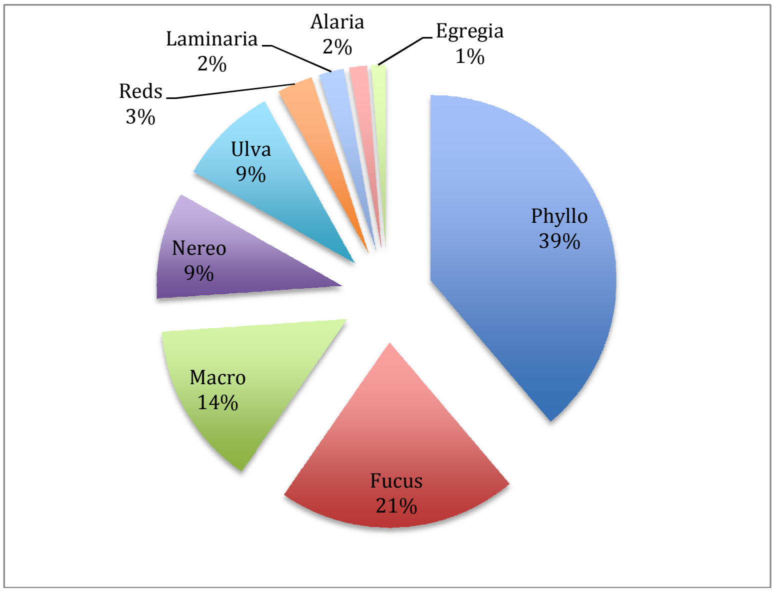

Figure 3. Dominance of species at all elevations with all sites included.

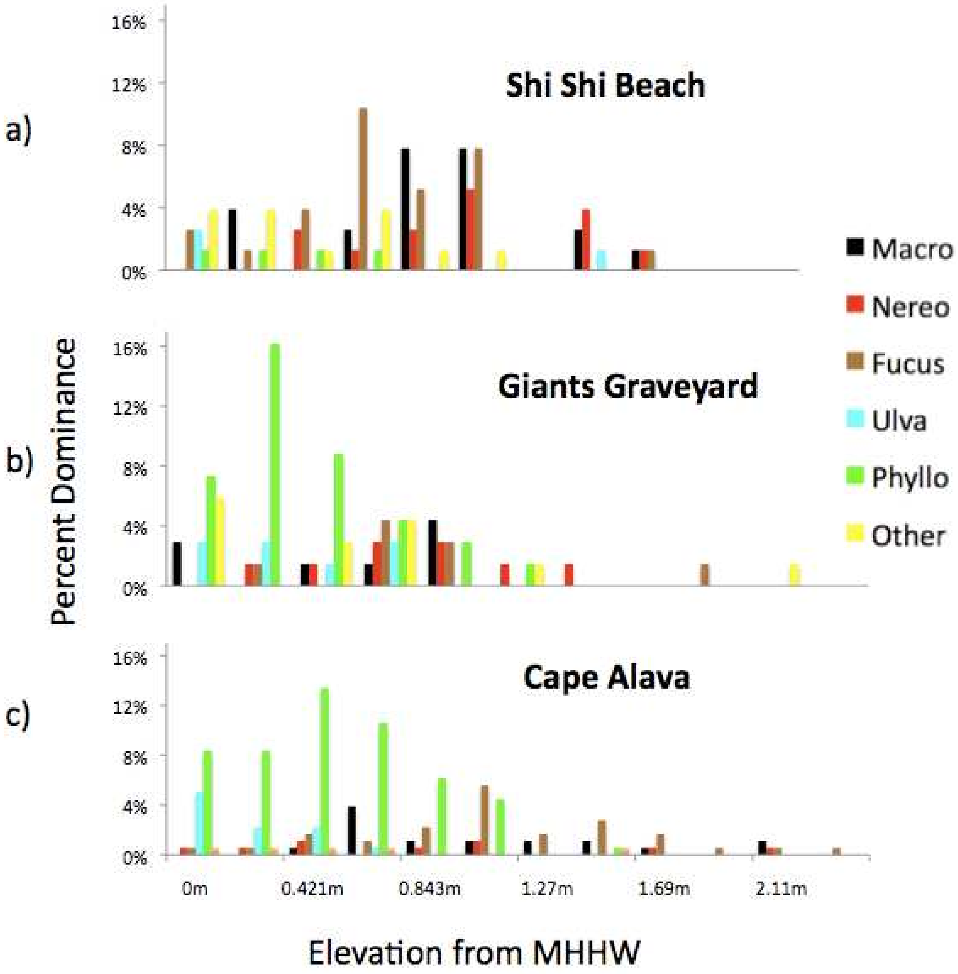

Figure 4. The five dominant species are shown by elevation at a) Shi Shi Beach b) Giants Graveyard and c) Cape Alava. The other three species and Reds complex are combined into the category of "Other". This figure shows spatial differences between species and relative percent dominance of species.

At all three sites several patterns begin to emerge. First, *Phyllospadix* and *Ulva* are found almost exclusively between MHHW and 1.5 m, quickly tapering off in percent dominance at and above this elevation. Secondly, the "others" group is usually found in this first meter of elevation change. Although the percent dominance of "others" varies between sites, this group was only found once above 1.5 meters. A third pattern that can be divulged is that the kelp species (*Macrocystis* and *Nereocystis*) are found relatively evenly at all elevations. Lastly, figure 4 shows a distinct peak in percent dominance of all species between MHHW and 1.5 m elevation at all sites.

If the dry weight of wrack samples is graphed against elevation from MHHW, a peak similar to percent dominance is found for biomass (Figure 5). Shi Shi Beach shows a distinct peak in dry weight per m^2 at approximately 1 meter. Giants Graveyard shows maximum dry weight at low elevations and deceasing with higher elevation. Cape Alava shows a similar but less pronounced peak as Shi Shi Beach.

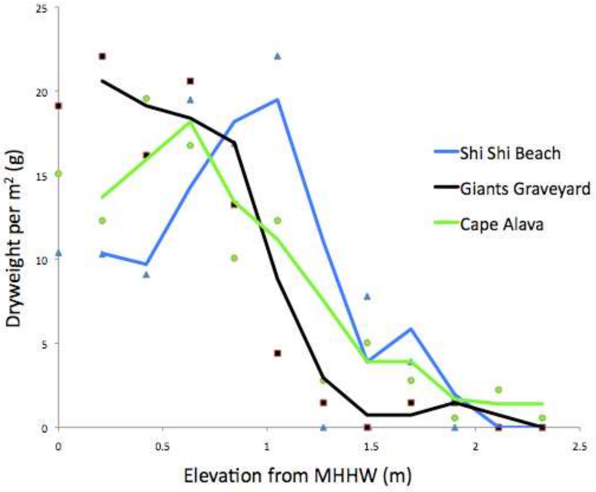

Figure 5. Dry weight distribution with elevation up from MHHW for Cape Alava, Giants Graveyard, and Shi Shi Beach. Trendlines shown are a moving average for two periods.

The three sites studied showed many differences compared to one another. For Cape Alava, shown as c) in Figure 4, from MHHW to roughly one meter the dominant species was *Phyllospadix*. *Ulva* was present at very low elevations and quickly disappeared after 0.8 meters. *Nereocystis* and *Macrocystis* were present at relatively equivalent dominance throughout most elevations and were deposited at higher elevations compared to other species. *Fucus* appeared around 0.4 meters, peaked at 1.1 meters and decreased at higher elevations, however it still remained the highest deposited dominant species at CA.

The patterns at Giants Graveyard were similar to those at Cape Alava as seen in Figure 4. *Phyllospadix* showed strong dominance at lower elevations and disappeared around 1 meter. *Ulva* distribution was also nearly identical to CA. *Macrocystis*, *Nereocystis*, and *Fucus* dominance showed similar dispersal, with *Fucus* being deposited at the highest elevations. The most striking difference between GG and CA was the increase in the “other” category. This group appears most often as a dominant in the zone from MHHW up to one meter, but was also present at higher elevations, showing the highest, dominant point beyond *Fucus* (Figure 4 c).

Shi Shi Beach (SS) was quite different than the above two sites. The most obvious difference was the grouping of percent dominance for all species at a higher elevation. The peak percent dominance for SS was between 0.6 and 1.2 meters, while for CA and GG the peak was more commonly between 0 and 0.9 meters. *Phyllospadix* was still present at lower elevations but was not nearly as dominant as it was at GG or CA. The “others” category was present, as at GG and disappeared after roughly one meter. *Macrocystis* and *Nereocystis* were more dominant, especially around one meter elevation and appear to be deposited at higher elevations more often than CA or GG. *Fucus* was distributed throughout all elevations with a major peak at 0.7 meters and remained equal to *Macrocystis* and *Nereocystis* at the highest elevations as seen in Figure 4 a.

Nitrogen Contribution by Dominant Species

Mean percent nitrogen was obtained for each species as well as the mean carbon to nitrogen ratios, as seen in Table 1. *Macrocystis*, *Nereocystis*, *Fucus*, and *Phyllospadix* had relatively similar percent nitrogen concentrations, however *Ulva* showed a higher concentration of nitrogen.

Table 1. Mean percent nitrogen for dominant species. Mean carbon to nitrogen ratios are also given for comparison.

	Macro	**Nereo**	**Fucus**	**Phyllo**	**Ulva**
Mean (St Dev) % N	1.44 (0.27)	1.53 (0.51)	1.57 (0.18)	1.66 (0.07)	2.95 (0.83)
Mean (St Dev) C:N	21.2 (6.1)	17.9 (6.4)	21.8 (2.2)	21.6 (0.8)	11.2 (2.6)

The carbon to nitrogen (C:N) ratio was compared to percent moisture as seen in Figure 6. Algae sampled (*Macrocystis*, *Nereocystis*, *Fucus*, and *Ulva)* show a negative relationship between the two variables. However, *Phyllospadix*, a seagrass, showed a relatively stable C:N ratio in respect to varying levels of percent moisture.

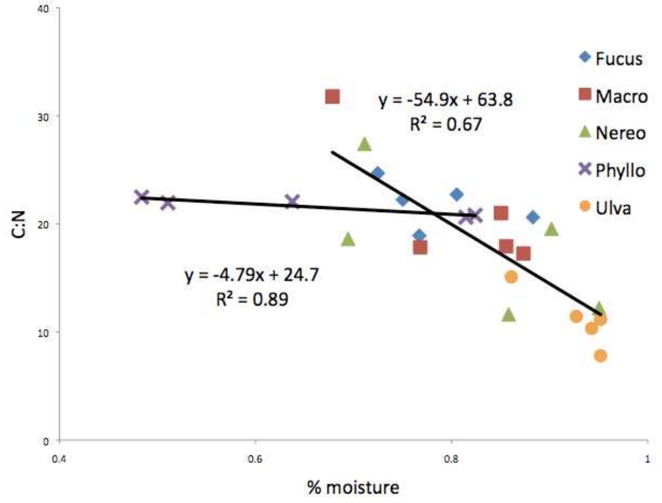

Figure 6. Relationship between carbon to nitrogen ratios and percent moisture. *Phyllospadix* (sea grass) is graphed separately from algal species.

Relationship Between Nitrogen Deposited and Percent Cover

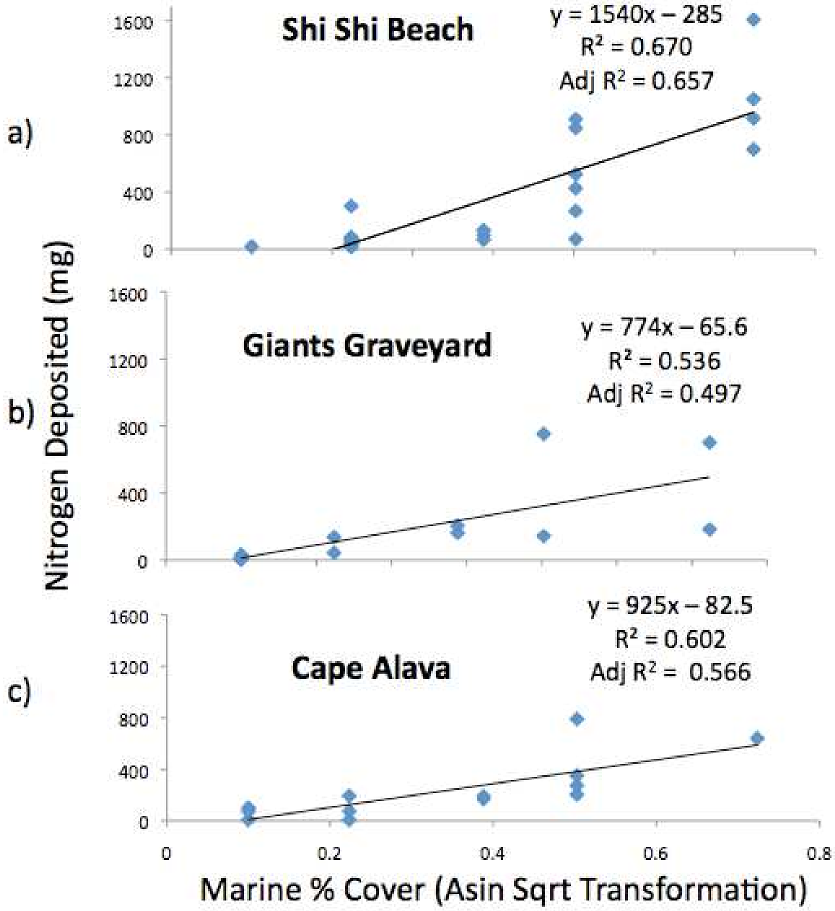

Figure 7. Relationship between nitrogen deposited and marine percent cover for a) Shi Shi Beach b) Giants Graveyard and c) Cape Alava. Marine percent cover has been arcsine-square root transformed.

Figure 7 shows nitrogen deposited as a function of marine percent cover. All sites show a positive linear relationship between nitrogen deposited and percent cover. Shi Shi Beach (Figure 7 a) presents the strongest relationship, ($R^2 = 0.670$, $F_{1, 19} = 39.3$, $p < 0.001$) showing higher nitrogen deposition per percent cover, than any other site. Cape Alava (Figure 7 c) shows the next highest nitrogen deposition ($R^2 = 0.602$, $F_{1, 11} = 16.6$, $p < 0.01$) followed by Giants Graveyard (Figure 7 b) ($R^2 = 0.536$, $F_{1, 12} = 13.8$, $p < 0.01$). These values and other statistics are given in Table 2.

Table 2. Regression statistics for each site with 95% confidence intervals for intercepts and slopes.

Site	**R^2**	**Intercept**	**95% CI: (Low - High)**	**Slope**	**95% CI: (Low - High)**	**n**
SS	0.674	-286	(-514) (-65.7)	1540	(1031) (2065)	19
GG	0.536	-65.6	(-238) (106)	774	(321) (1227)	12
CA	0.602	-82.5	(-279) (114)	926	(426) (1425)	11

Total Nitrogen Deposited at Each Site

Table 3. Mean percent covers and regression equations for all three sites with total grams of nitrogen deposited per meter squared by site.

Site	**Mean % cover per m^2 (St Dev) ("x" in equation)**	**Regression Equation**	**Total Nitrogen (g N per m^2) (St Dev)**
SS	3.93 (9.76)	y = 1540x - 285	5.77 (14.7)
GG	9.29 (22.7)	y = 774x - 65.6	7.12 (17.5)
CA	26.5 (33.9)	y = 925x - 82.5	24.4 (31.3)

Total nitrogen deposition is a function of two factors: Percent nitrogen per sample and percentage of area covered by wrack. Cape Alava showed the highest value for total nitrogen deposited at 24.4 g N/m^2. Giants Graveyard and Shi Shi Beach present much smaller values for nitrogen deposited at 7.13 N/m^2 and 6.85 N/m^2, respectively. A Tukey multiple comparison analysis was conducted to find the relationship between sites. The analysis of variance showed that total nitrogen deposited varied between sites with Cape Alava having higher nitrogen deposition than Shi Shi Beach or Giants Graveyard (CA> SS~=GG; $F_{2, 881} = 65.8$; $p<0.0001$). Although, Shi Shi Beach showed the highest percent nitrogen per sample (Figure 7 a), the mean percent cover at that site was the lowest sampled (Table 3). Giants Graveyard showed less than half the percent nitrogen per sample than Shi Shi Beach had, but had a higher percent cover, leaving the total nitrogen value greater than Shi Shi Beach. Cape Alava showed a value for percent nitrogen per sample in-between GG and SS, but had a much higher percent cover value. This significant difference in percent cover led to Cape Alava having the highest total nitrogen per meter squared of all sites.

DISCUSSION

Five seaweeds were determined to be the dominant species found in wrack deposits. Those species, in descending abundance are: *Phyllospadix* spp. (39%), *Fucus gardneri* (21%), *Macrocystis integrifolia* (14%), *Nereocystis luetkeana* (9%), and *Ulva* spp. (9%). There was variation between sites in species dominance and in elevational distribution. Shi Shi Beach showed the greatest diversity and was dominated most often by *Fucus*. Giants Graveyard was dominated most often by *Phyllospadix,* and showed high levels of *Phyllospadix* deposition at lower elevations but little deposition at higher elevations. Cape Alava was also dominated by *Phyllospadix* but showed a more even distribution of seaweeds from low to high elevations.

At all sites dry weights of wrack depositions were highest at elevations from MHHW to approximately 1.5 meters. This shows that the majority of biomass, and nitrogen is deposited is within this elevation zone. Since *Phyllospadix* spp. were generally the dominant species in this zone, this genera is probably most influential to nitrogen deposition from MHHW to 1.5 meters upland of MHHW. Above this elevation, *Fucus, Macrocystis,* and *Nereocystis* were dominant and probably most influential to nitrogen deposition.

Nitrogen concentrations differed slightly between species as shown in Table 1. *Ulva* showed the highest percent nitrogen concentration followed by *Phyllospadix, Fucus, Nereocystis,* and *Macrocystis*. However, *Ulva* deposition was dispersed and rare compared to other species, leading to no functional difference in nitrogen concentration between species in wrack deposits.

A difference between species was found in C:N ratios compared to percent moisture. Algal species showed a marked decrease in nitrogen over time, while *Phyllospadix* (sea grass) showed a relatively stable nitrogen concentration. This means that *Phyllospadix* could provide a more stable source of nitrogen over time.

Each of the three sites studied showed variance in the total amount of nitrogen deposited. Cape Alava had significantly higher total nitrogen deposited per meter squared than Giants Graveyard or Shi Shi Beach, who were roughly equivalent. Two factors influenced the nitrogen deposited: Mean percent deposition on the beach (Table 3) and nitrogen percentage per unit area. The pattern observed here is likely driven by mean total deposition of wrack, as the relationship between % cover and nitrogen biomass does not vary by site given the limitations of our sampling.

Percent Cover

Cape Alava had a significantly higher percent cover of wrack than Giants Graveyard or Shi Shi Beach. Giants Graveyard and Shi Shi Beach were found to be roughly equivalent. The differences in percent cover can be, in part, attributed to beach morphology and source populations.

The slope, area, and consequential size of a beach are all important influences. All three sites had similar slopes but Shi Shi Beach had the lowest at an average of 3.95°, followed by Cape Alava at 4.03°, and Giants Graveyard at 4.06°. The distance from MHHW to the tree line also varied between the three sites. Cape Alava had the longest average distance of 33m, while Shi Shi Beach and Giants Graveyard both had an average distance of 30m. Beaches with shallower slopes may have more surface area by elevation, which allows for more time and space for wrack material to be caught or snagged on the beach. It is unknown if differences in slope and distance from MHHW to the tree line were important factor determining wrack species during this study, but others (Orr et al. 2005) have found that, in general, wrack deposition in proportional to surface area of the beach.

Figure 5 shows the majority of biomass being deposited between MHHW and 1.5 m above MHHW. It follows than if the majority of biomass were deposited here, the greatest percent covers would also be found between these elevations. It is suspected that wrack depositions above 1.5 m are more permanent, while depositions below 1.5 m are temporarily deposited and heavily influenced by wave action.

Source populations for the wrack deposits are of great influence on the dominant species found, and biomass of wrack (Orr et al. 2005; Polis and Hurd 1996). Each of the beach sites surveyed in this study was adjacent to a rocky headland, which was also surveyed for algal abundance and diversity. Current studies are underway identifying these headlands as the source populations for the beaches used here.

Dominant Species

There was variability in species abundance and assemblage between sites and within sites. This variability is likely due to a combination of factors. Beach morphology and source populations are important factors as discussed above for inter-site differences. Some of the intra-site differences may be attributed to seaweed morphology.

Buoyancy characteristics play a large part in determining composition of wrack species in Puget Sound, Washington (Mumford 2007) and greater British Columbia (Orr et al. 2005). Of the five dominant species determined in our study, two were kelp: *Macrocystis integrifolia* and *Nereocystis luetkeana*. Both these types of kelp have floatation adaptations, which was hypothesized to lead to average higher depositions compared to other dominants. The evidence found contributed to this hypothesis. When considering Figure 4, *Macrocystis* and *Nereocystis* are both dominant in wrack deposits at higher elevations compared to other species. This pattern is shown particularly well at Cape Alava (Figure 4 c). In addition to these kelp species, *Fucus* was also found as the dominant in many higher elevation wrack deposits. *Fucus* also displays floatation adaptations during certain times of the year when the species undergoes morphological changes for reproduction.

Nitrogen percentages for each dominant species were also determined. The hypothesis tested was that kelp would provide the most nitrogen contributions to each wrack deposit. This was not found to be completely true at the sites sampled. The nitrogen percentages in Table 1 show that *Ulva* was actually highest in nitrogen at 2.95%. However, since *Ulva* was so dispersed and rarely the dominant species, its high nitrogen percentage did not significantly contribute to the total nitrogen deposition. Therefore, functionally there is no significant difference in nitrogen percentage between *Ulva*, *Phyllospadix, Fucus, Nereocystis,* and *Macrocystis*.

Breakdown of seaweed material and degradation of nitrogen over time is an important consideration for the transfer of nutrients between ecosystems. As shown in Figure 6, the carbon to nitrogen ratio (C:N) of each species changes with percent moisture. Percent moisture can be thought of as a proxy for time. High moisture content will be reflected in newly deposited wrack samples, and over time as the wrack deposit dries, percent moisture will decrease. As moisture percentage decreases in these seaweeds, C:N ratios increase, indicative of falling nitrogen concentrations. The algal species *Ulva*, *Fucus, Nereocystis,* and *Macrocystis* all show a negative relationship between C:N and percent moisture. However, *Phyllospadix*, a seagrass, showed relatively stable C:N ratios in respect to varying levels of percent moisture. Although nitrogen degradation is still present in *Phyllospadix,* it occurs at a rate much less than that of the other dominant species. As such, beaches with wrack deposition dominated by *Phyllospadix* could provide a more stable pool of nitrogen that could be utilized by terrestrial systems over a greater span of time. This could have profound impacts on nitrogen usage by terrestrial species over time, and reveals *Phyllospadix* as a more important dominant species than previously expected.

Contributions by Species to Nitrogen Subsidies

To determine contributions made by each species we must consider nitrogen percentage and how often a species was found as the dominant species in wrack deposits (percent dominance). *Ulva* was only dominant 9% of the time and often found at lower elevations were it was out-numbered by other species (Figure 4). Therefore, we can conclude that although *Ulva* was relatively high in nitrogen, the contribution made to the total nitrogen deposited through wrack, was low. *Phyllospadix* was the most dominant species found (39%). This species also displayed the second highest percent nitrogen value although significantly less than *Ulva*. *Phyllospadix* also experiences nitrogen degradation at a much slower rate that other dominant seaweeds. Based on these factors, we deduce that *Phyllospadix* makes a large contribution to the total nitrogen subsidy on a beach. If elevations are considered, *Phyllospadix* may supply the majority of nitrogen at elevations less than 1.5 m above MHHW, especially at Giants Graveyard and Cape Alava.

Fucus, Nereocystis, and *Macrocystis* all are similar in percent dominance and nitrogen percentage. At lower elevations these species make a contribution to total nitrogen, especially at Shi Shi Beach (Figure 4 a). However, at Giants Graveyard and Cape Alava they are shadowed by *Phyllospadix* abundance at lower elevations. In contrast, at higher elevations *Fucus, Nereocystis,* and *Macrocystis* are the most abundant species and almost are entirely responsible for the nitrogen deposited at elevations above 1.5 m above MHHW. Thus, we concluded that *Fucus, Macrocystis,* and *Nereocystis* are influential species to nitrogen subsidies above 1.5 m at all sites.

The hypothesis that kelp makes the largest contribution to nitrogen subsidies is neither bolstered nor negated. Rather, it must be more specific. Kelp species do appear to make a significant contribution to the total nitrogen deposited through wrack at elevations above 1.5 m from MHHW. As well, if the term “brown alga” were used instead of “kelp” then *Fucus* could be included and the hypothesis would be more appropriate. At elevations less than 1.5 m above MHHW, it appears that *Phyllospadix* makes the most significant contribution to nitrogen on the beach.

Spatial Variation

All sites showed a positive relationship between percent cover and nitrogen deposited (Figure 7). It is only logical that this relationship is positive, but the fact that it appears linear at the resolution our data gives, is of interest. Percent cover can be thought of as a proxy for biomass. Thus, increasing biomass yields more nitrogen with no apparent saturation point. However, this conclusion is subject to the limitations of the sampling methods used here and does not rule out the possibility that an exponential model would appear if more data were collected.

Considering all quadrats sampled, analysis of variance showed that total nitrogen deposited varied between sites with Cape Alava having higher nitrogen deposition than Shi Shi Beach or Giants Graveyard (CA> SS~=GG; F 2,881=65.8; p<0.0001). This pattern is likely driven by total deposition of wrack because the relationships between percent cover and biomass or nitrogen biomass do not vary substantially by site.

CONCLUSION

Our study concludes that there are five dominant seaweed species that contribute to the nitrogen subsidies provided through wrack deposition at our sites. Percent nitrogen concentrations between these species does differ, but not to a degree that significantly influences the total nitrogen deposited. The driving force controlling total nitrogen deposited appears to be the surface area covered by wrack deposits on the beach. Percent cover, as shown in Table 3, makes an important difference in the total nitrogen subsidy.

Additionally, the majority of biomass was deposited between MHHW and roughly the first 1.5 m of vertical elevation gain. Lesser amounts of wrack were deposited above this level. It is unknown if the wrack deposited between MHHW and 1.5 m is important to the flow of nutrients from marine to terrestrial because high tides may deposit and remove this material quickly. However the wrack deposited above 1.5 m above MHHW may be more permanent and could play a more critical role in nitrogen sharing and usage.

The information gained here shows that nitrogen subsidies are present on beaches, are provided by wrack deposition, and could be used by terrestrial systems. If terrestrial systems are dependant on the subsidies of nitrogen provided by wrack deposits then efforts should be made to monitor and protect the wrack deposited into these systems. The focus of this study was to look at this budget during the summer months (June through August) but to fully understand the nitrogen budget, information is needed about year-round levels and fluxes. As well, source populations and dominant species will need to be identified further and examined.

Further Studies

Although the data gathered here is a valuable part of understanding inter-ecosystem nutrient flow, it is just the beginning of information that needs to be gathered. A major component that remains unknown is how deposition of wrack changes over time. We determined a budget for nitrogen during the summer months at our sites, but to fully understand these systems we will need complete knowledge of how wrack and nutrient levels change throughout the year. Budgets for the winter season when storms may dislodge large amounts on algae from the substrate could be especially important.

There are currently on-going studies, in conjunction with this one, taking place in Olympic National Park at the same sites used here. One such study is analyzing nitrogen concentrations in Sitka spruce that are located at the coastal tree line, and comparing those concentrations with spruce that are located further inland. Another study is comparing how the abundance and assemblage of arthropods changes from a specified distance below the tree line to a distance above the tree line. These arthropods are suspected to be one of the main ways that nutrients are transported between ecosystems.