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Seasonal Variations in and Observations of Landslide Impacts on the Algal Composition of a Puget Sound Nearshore Kelp Forest

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Abstract

A medium scale landslide (2153 m^3) deposited sediment on to a intertidal beach on the north side of Point Williams, Seattle, Washington on 4 April 1991. Within 23 days of the slide, high tides and rain carried 77% of the sediment to nearshore waters and north through a seasonal kelp bed immediately adjacent to the slide area. Transects were placed in north and unimpacted south kelp beds and monitored seasonally for algal community and densities. Significant differences in north and south kelp bed *Costaria costata*, *Laminaria* sp., and *Nereocystis luetkeana* densities occurred during spring. No other community or density differences were found. Irradiance values for the two beds differed during winter months but were similar for the rest of the year. Significant differences in spring kelp densities may be attributed to short term impacts of landslide sediment introduced to the kelp bed during early kelp growth stages. However the landslide did not appear to effect the kelp community after the observed spring depression. Larger landslides may have more extensive impacts.

Introduction

Sedimentation is an integral process in coastal systems of the Northeast Pacific. Seasonal rainfall combine with steep drainages to transport sediment to estuarine and marine coastal waters. These sediments are critical for a multitude of beach and estuarine dynamics, including beach nourishment and nutrient transport (Bavestrello *et al.* 1991, Stow and Chang 1987). Upland activities, including logging and land development, often result in an increase in the volume of sediment transported to adjacent streams and rivers. The negative impact of increased sedimentation has been repeatedly documented for fresh water fisheries and wildlife resources, and is a constant concern of resource managers (Chang and Stow 1988, Reid and Dunne 1984, Stow and Chang 1987, Taylor 1983).

Research in other regions has shown that light is critical for growth, and that turbidity and sedimentation can be one of the most critical forms of disturbance impacting species of nearshore kelps. Turbidity from sediment in the water column may be the primary factor causing decreased light levels in nearshore waters (Dean 1985). Turbidity induced lower light levels occuring during recruitment windows may result in subthreshold light levels for gametogenisis and sporophyte production. Severe and chronic light reductions may lead to long term disappearance of adult kelp plants and subsequently result in long term shifts in dominant species and community composition of marine and estuarine algal communities (Cole and Sheath 1990, Dean and Dysher 1983, Kimura and Foster 1984, Thom 1978). Sedimentation also can also result in gametophyte smothering and scouring, and lead to increased mortality and changes in *Macrocystis pyrifera* Linnaeus and *Laminaria* sp. densi-

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ties and distribution (Dean and Deysher 1983, Devinney and Volse 1978). Impacts of upland landslides on nearshore habitats, associated suspended sediments, and sedimentation effects on northwest kelp beds have not been previously studied.

Nereocystis luetkeana Mertens kelp beds are one of the dominant vegetated habitats in Puget Sound, Washington (Thom and Hallum 1990). They are critical habitats for a number of important commercial and sport species including salmonids (*Oncorhynchus* spp.), rockfish (*Sebastes* sp.), lingcod (*Ophiodon* sp.) and Dungeness and rock crab (*Cancer* spp.). The algal communities of Puget Sound kelp beds shift seasonally, and consist of the annual brown kelp *Nereocystis luetkeana* overstory and a varied understory of Laminariales and fleshy red algae (Hodgeson and Waaland 1979, Thom 1978, Thom and Albright 1990, Thom *et al.* 1976). Seasonal recolonization varies annually. Physical factors including light, water temperature, and substrate determine the algal composition of these beds (Thom and Albright 1990, Thom and Hallum 1990). *Nereocystis luetkeana* and Laminariales recolonization begin in early spring months with the onset of sporophyte growth (Foreman 1984). Initiation of gametogenesis and sporophyte growth is controlled by light, and will be delayed at suboptimal light levels (Hsaio and Druehl 1973).

In April 1991, a landslide occurred on a steep slope of Point Williams, located in Seattle, Washington (Fig. 1). The toe of the landslide covered an intertidal beach just northwest of the slide area. Intense rainfall, current, and wave action concomitant with the slide carried sediment off the beach and northward parallel to shore, and into a seasonal *Nereocystis leutkeana* bed located immediately adjacent to the slide area. Plumes of sediment were seen over the kelp bed area for weeks following the slide. Another kelp bed, located on the south side of the Point and south of the slide area, was not affected by the slide (pers. obs.).

If sedimentation impacted the early gametophyte and sporophyte development of kelps in the northern kelp bed, differences in understory algal composition and densities of brown algae between the impacted and unimpacted beds would be predicted. This paper is the product of a one year study documenting the seasonal changes in the algal composition of these two subtidal Puget Sound kelp beds, and differences in algal composition and density in the northern kelp bed relative to the southern kelp bed that might be due to increased turbidity and sedimentation from the April 1991 landslide.

Material and Methods

The study site is located on the east side of the Central Main Basin of Puget Sound (Downing 1983) and consists of a steep headland bluff on the north side of Point Williams, Seattle, Washington, (lat. 47°31'50" N, long. 122°24'2" W), and two subtidal kelp beds located just offshore to the north and south of the Point (Fig. 1).

Landslide documentation

The failed slope, which gave way on 4 April 1991, was surveyed within 23 days of the slide to determine the volume and nature of sediment contributed to the nearshore habitat. Reference points were established in the axis of the landslide at 6 meter intervals from the top of the landslide scar to where material first deposited at the toe of the slope. At each reference point, a transect was established normal to the axis of the landslide and surface elevations were determined at 3 meter intervals from the axis to both edges of the landslide using a meter tape and inclinometer. From this survey, 98 data points representing the geometry of the landslide scar surface were obtained. These data were then used to calculate the volume of material displaced from the hillside.

The particle size distribution of the landslide sediment was determined from field verification of the soil profile description completed by Snyder *et al.* (1973).

Algal community

Both subtidal kelp beds are located in five meters of water, are approximately 10 meters wide, 500 meters long, and are located approximately 15 meters offshore. Both are located on very gradual slopes, bordered on the landward side by cobble substratum and medium fine sand with eelgrass beds on the seaward side, and are typical of Puget Sound kelp beds. The two beds are approximately 750 meters away from each other and are separated by Point Williams. The bed exposed to landslide sediments is located in a shallow cove to the north of the point (hereafter called the north kelp bed), the unimpacted bed in a shallow cove, known as Fauntleroy Cove, to the south of the point (hereafter called the south bed; Fig. 1). Net drift and surface currents at Point Williams and in the northern cove are northerly, with a net flow of 6.36 cm s^{-2} (Chrzastowski 1982, Cox *et al.* 1984). The southern tip of the north bed is located approximately 20 meters from the slide area.

Kelp sampling was done with the use of SCUBA. Two permanent thirty-meter transect lines marked at meter intervals were placed parallel to shore in the center of each of the north and south kelp beds. Lines in the north

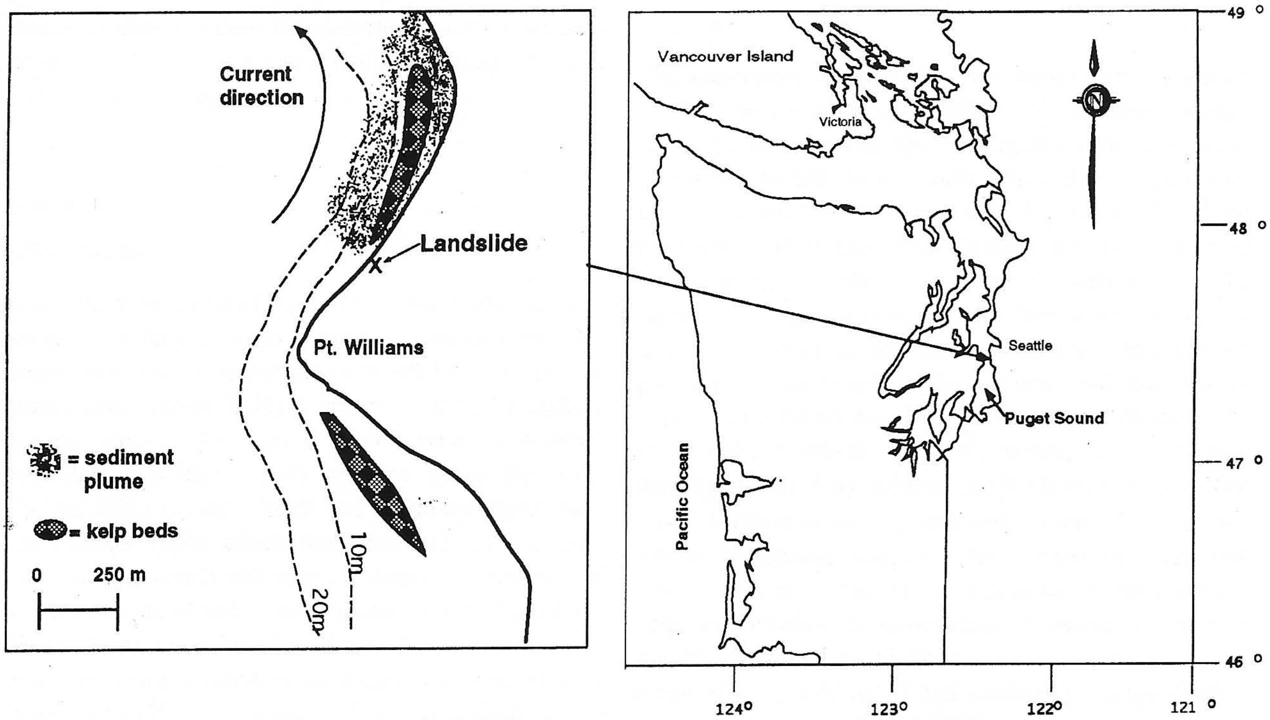

Fig. 1. Study site off Point Williams, Seattle, Washington.

bed were put out in January 1991 and first sampled in February 1991, prior to the landslide. South kelp bed lines were put out and sampled in late April 1991, immediately after the slide. Beginning in April 1991, transects in both beds were sampled once every season (at two to four month intervals). During each sampling period, both kelp beds were sampled within a week of each other. Five 1.0 m^2 quadrats were sampled randomly from each transect line for substratum and understory vegetation percent cover and density of brown algae. All brown algae were identified to the lowest possible taxon. Red algae were grouped and assessed simply as 'fleshy reds'. Total and relative percent cover data were recorded. If 25% or more of the total vegetation in each quadrat appeared to overlap, percent cover data were recorded in vegetation in two layers:

1. 0−15 cm off substratum and
2. 16 cm−1.0 meter off the substratum.

If not, data were recorded from substrate to 1.0 meter off the substrate. Total percent cover for all non-encrusting vegetation with a total area greater than 10 cm^2 was recorded first for all vegetation in the quadrat. Relative percent cover of each taxonomic group was then recorded. After percent cover was recorded, blades of algae was moved out of the way and densities of brown kelps recorded. Density was defined as the number of each species with both holdfast and stipe within the quadrat.

Percent cover and density data were averaged for each sampling date and bed. Single factor ANOVAs were conducted to determine significant differences of dominant brown algae densities in the two beds during each season.

Irradiance

The north kelp bed is located below a steep bluff, therefore direct sunlight (irradiance) does not illuminate the bed until the sun angle elevation from the horizon reaches 21.8 degrees. The south kelp bed is unobstructed from direct irradiance regardless of the sun angle elevation. It was therefore necessary to estimate the difference in mean daily direct surface irradiance (Ly d^{-1}) between the two kelp beds throughout the year. Using a model given by List (1971), the mean daily direct surface irradiance (Ly d^{-1}) was calculated for the north and south kelp beds using a solar constant of 1.94 cal cm^{-2} min^{-1}; an atmospheric transmission coefficient of 0.72, and an optical airmass number equal to 1/sin (sun angle elevation in degrees). Direct irradiance (Ly d^{-1}) was calculated hourly for sun elevation angles greater than zero for each day of the year. Daily irradiance totals were summed for the month and averaged. Because total irradiance is equivalent to diffuse irradiance when clouds obscure the sun (Campbell 1977) it was assumed that there was no difference in total irradiance between the two kelp beds during overcast sky conditions.

Surface irradiance values for each month were next converted to irradiance at 5 meter depth assuming 5% light transmission (Lüning 1981).

Results

Sedimentation

During the first week of April 1991, the study area experienced a relatively high-intensity rainstorm which delivered 104 mm of precipitation in 48 hours (National Climate Data Center 1991). Concurrent with the highest intensity rainfall (2.8 mm h^{-1}) observed on 4 April 1991, the steep (62 degree) hillslope above the north kelp bed failed and developed into a shallow rapid landslide (Varnes 1978) which delivered 2153 m^3 of sediment onto the beach and into the nearshore waters. Of the total volume of sediment evacuated by the landslide, 77% (1658 m^3) was introduced into the nearshore marine waters within 23 days of the slide event. The remaining 495 m^3 (23%) was deposited on the upland slopes above the high tide line and continued to contribute sediment to the nearshore for up to a year after the slide.

The landslide originated from a hillslope composed of Alderwood series soils characterized as a gravelly sandy loam overlying a weakly consolidated till layer. The Alderwood soil series is dominated by gravel size particles with 65% of all particles ranging between 76.0 mm and 2.0 mm. Sand size particles (2.0 mm−0.42 mm) represent 23% of the soil profile. Silt and finer (< 0.42 mm) sized sediment composes 12% of the Alderwood soil profile.

Algal composition of kelp beds

Percent cover

Layering was necessary in only three quadrats throughout the study. All three were in the north kelp bed in the summer sampling. Data are therefore presented as percent cover from 0.0 to 1.0 meter off the substrate.

Algal percent cover, density, and composition of the two beds were very similar and varied dramatically with season. In the north kelp bed, average percent cover of total vegetation fluctuated from 20% in the autumn and winter (dominated by fleshy reds and *Costaria costata* C. Agardh) to 100% in the summer (of which 80% was *C. costata*; Fig. 2). Percent cover in the southern kelp bed followed similar trends (Fig. 2). Average total vegetation percent cover ranged from 90% in the summer (dominated by *C. costata*) to 35% in the autumn (*C. costata*, *Nereocystis luetkeana* and fleshy reds were equally dominant) and 40% in the winter, of which 90% was fleshy reds.

Density

The understory of each bed was dominated seasonally by five brown algae, *C. costata*, *N. luetkeana*, *Laminaria* sp., *Desmarestia ligulata* Lightfoot and *Desmarestia viridus* Müller. In the north kelp bed, average densities of all species were less than 1 plant m^{-2} in both February of 1991 and 1992. *Costaria costata* dominated in the spring and summer (average 8 plants m^{-2} and 11 plants m^{-2}, respectively, Fig. 3). *Nereocystis luetkeana* densities peaked in the summer in the north bed (6 plants m^{-2}) declined in the autumn, and dropped to 0 m^{-2} again by winter (Fig. 3). *Laminaria* sp. densities peaked at 2 plants m^{-2} in the summer, dropped to less than 1 plant m^{-2} by autumn and 0 plant m^{-2} by winter (Fig. 3). *Desmarestia ligulata* was present in low densities in the spring, summer, and autumn (average less than 1 plant m^{-2}; Fig. 3). Kelp densities in the southern kelp bed followed the same trends. *Costaria costata* was dominant and had the highest densities in the spring (average of 17 plants m^{-2}) and summer (average density of 12 plants m^{-2}), dropped off sharply to 2 plants m^{-2} in the autumn and 0 plants m^{-2} in February 1992. As in the north bed, *N. luetkeana*, *Laminaria* sp., and *D. ligulata* had the highest densities in the spring and summer, which then declined to 0 plants m^{-2} in winter 1992 (Fig. 3).

ANOVA of densities revealed a significant difference between north and south bed *C. costata*, *Laminaria* sp., and *N. luetkeana* densities for April 1991 ($F = 7.12$, $p = .011$; $F = 5.96$, $p = .02$; and $F = 6.29$, $p = .017$, respectively with 1,18 degrees of freedom). No other significant differences were found in algal densities of the two beds.

Substrate composition of the two beds was similar. North bed substrate was made up of 66% cobble, 14% gravel and shell, and 18% sand. South bed substratum consisted of 58% cobble, 20% gravel and shell, and 20% sand.

Irradiance

Estimates of direct irradiance (Ly d^{-1}) indicate that the northern kelp bed received less direct irradiance than the southern bed throughout the year (Fig. 4). The largest difference in estimated direct irradiance between the two beds occurred in January, November, and December, when the southern kelp bed received approximately twice as much solar radiation as the northern kelp bed. Differences in direct irradiance between the two beds decreased in February, and were relatively small from March to October. Average surface irradiance during spring months ranged from 300 Ly d^{-1} in March to almost 600 Ly d^{-1} in May. Spring irradiance at depth

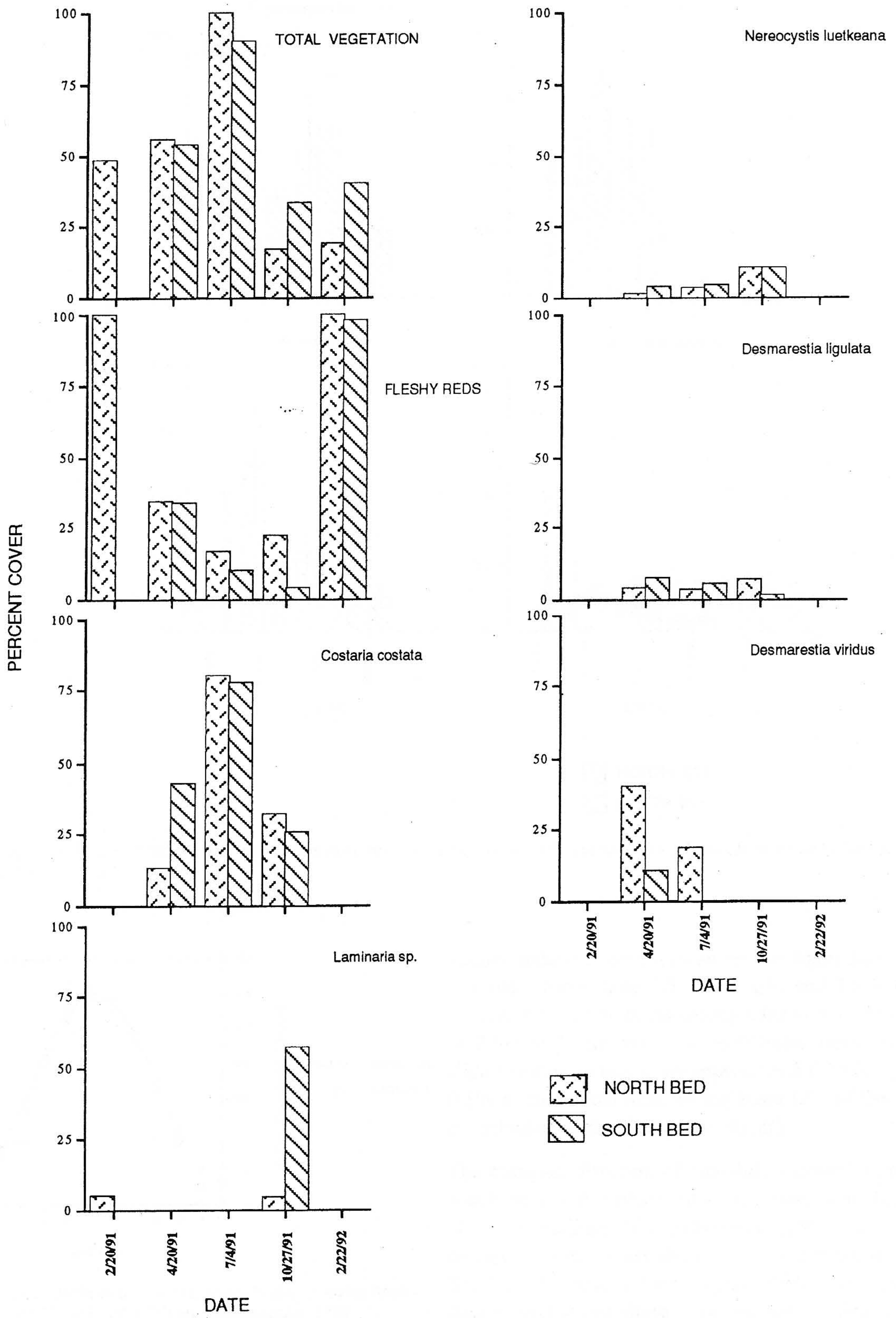

Fig. 2. Average total and relative percent cover for dominant understory vegetation of Point Williams north and south kelp beds, 1991–1992. ns = not sampled.

ranged from 12.5 Ly d^{-1} in March to 27 Ly d^{-1} in May. Surface and subtidal irradiance peaked in June at around 600 Ly d^{-1} and 30 Ly d^{-1}, respectively, and dropped to 200 Ly d^{-1}, and 10 Ly d^{-1} by October. Due to a low sun angle the north kelp bed received no direct irradiance in December.

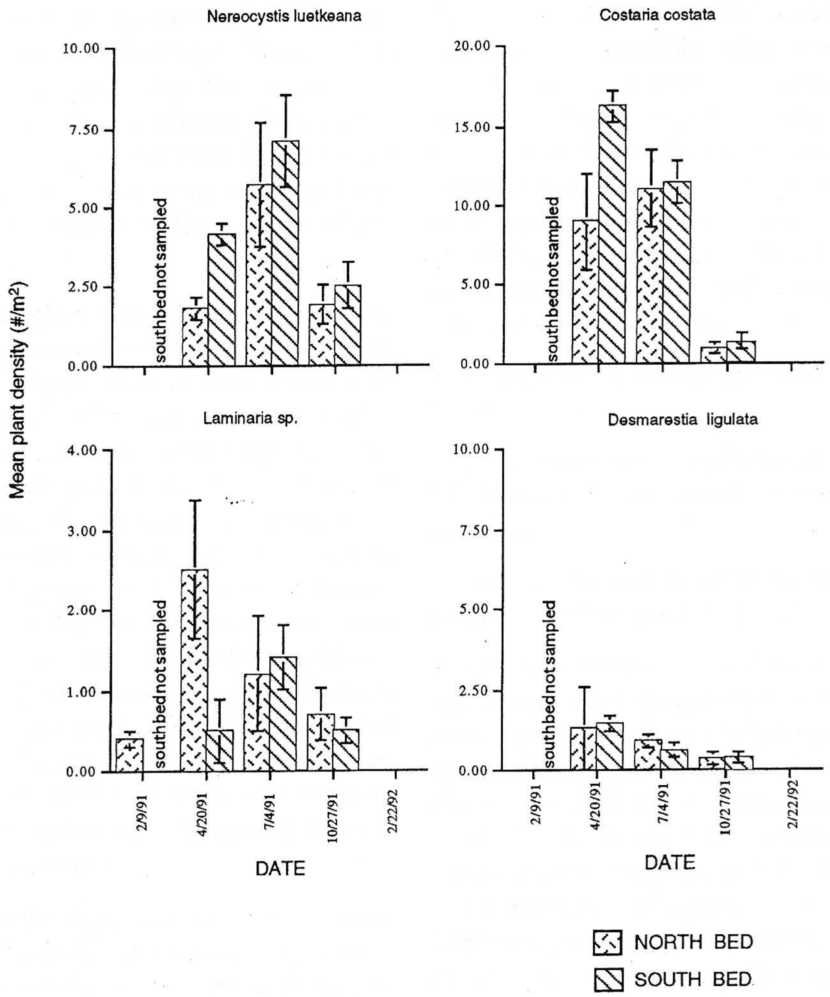

Fig. 3. Average densities + 1 SE for dominant understory brown vegetation in north and south kelp beds off of Point Williams, Seattle, Washington, 1991–1992.

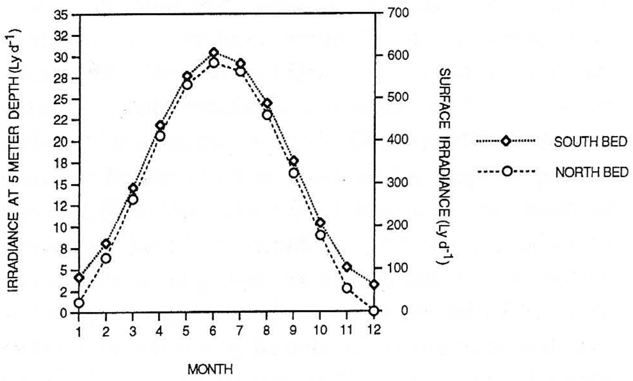

Fig. 4. Estimated mean daily surface and subtidal (5 meter depth) irradiation (Ly d^{-1}) at Point Williams, Washington, 1991.

Discussion

The relative contribution of sediment of the 4 April 1991 landslide to the Main Basin of Puget Sound is small when compared to the annual contribution of sediment from other sources. Lavelle *et al.* (1985) report the total annual sediment contribution in the Main Basin from riverine sources to be 7.0×10^{11} g/yr and 3.8×10^{11} g/yr from bluff erosion. Assuming a mean particle density of 2.6 g/cm^3, the sediment contributed from the landslide reported in this study represents 5.6×10^9 g/yr, or 0.5% of the annual total for the basin (2% of the annual contribution of the Duwamish River).

The transport direction of landslide-supplied suspended sediment visually observed in the north kelp bed supports the findings of Chrzastowski (1982), who documented a northerly net-shore drift along Point Williams. The fate of coarse sediment (gravels and cobbles) introduced into the nearshore zone was not documented, but observations of sediment transport rates along Point Williams by Schwartz *et al.* (1989) suggest an eventual northward movement at a mean rate of 6000 m^3/yr.

The pronounced seasonal differences in algal composition and density observed in this study are consistent with results of other work. Thom and Albright (1990) found total biomass to range from 3×10^3 kg dry weight in winter to 66 × 10^3 kg dry weight in the summer for a 2.24 km^2 area of Seahurst bight. These authors concluded that light is the driver for the seasonal changes. In separate studies of southern and central Puget Sound kelp beds, Hodgson and Waalund (1979) and Thom (1980), documented species composition and seasonal changes that are similar to the findings of this work.

Physiological and morphological adaptations within algal groups allow this seasonal partitioning of the habitat. Red algae have the largest range of light tolerance of all photosynthetic plants. Many are adapted to exploit seasonally available substratum, and are the most productive in winter (Cole and Sheath 1990). Numerous brown algae, including *N. luetkeana*, are annuals adapted for fast seasonal colonization and growth, similar to terrestrial weeds (Foreman 1984, Reed 1990). Laminarian spores, gametophytes and sporophytes also have very specific light requirements for photosynthesis and growth which allow them to dominate subtidal habitats during spring and summer months (Amsler and Neushul 1991, Lüning 1981, Lüning 1980). The large morphological differences of these two seasonally dominant groups transform the kelp beds into structurally different habitats in winter and summer.

Large scale shifts in the algal community of the north kelp bed due to the landslide were not observed. Instead species composition of the north bed resembled the south bed, and had the same dominant species within each season after the landslide. Densities of the three dominant species were, however, significantly different from the south kelp bed in spring. Sporophyte production in laminarian algae is dependant on threshold irradiance, temperature, nutrients, and sediment flux (Dean 1985, Deysher and Dean 1986, Lüning 1980). Of these four, only irradiance and sediment flux would be different between the two beds. Density differences may therefore be due to either a delay of sporophyte growth due to differential surface irradiance at the two beds, or caused by landslide turbidity. Sporophyte production and benthic algae growth are light initiated in late winter and early spring months (Hsaio and Druehl 1973, Thom 1978). Production may be delayed by sub-threshold light levels (Hsaio and Druehl 1973). Thom and Albright (1990) state that in Puget Sound, illuminance of 4 E m^{-2} d^{-1}, which occurs in March, will initiate benthic plant growth, and that saturation occurs at approximately 15–20 E m^{-2} d^{-1}, in May and June. Lüning (1981) reported that young *Laminaria* sp. sporophytes require a minimum of 0.1030 Ly d^{-1} for growth, and 6.18 Ly d^{-1} for saturation growth rates. Comparing these numbers to surface and subtidal irradiance estimated for the two kelp beds of this study we conclude that, in the absence of differential turbidity, growth threshold and saturation values are exceeded in both beds by January and February, respectively. In his discussion on Puget Sound growing season, Strickland (1983) stated that irradiance in January was 100 Ly d^{-1}, increased to around 400 Ly d^{-1} in April, peaked at 600 Ly d^{-1} in July, and dropped to less than 50 Ly d^{-1} by December. Overlapping the results of Lüning (1981), Strickland (1983), Thom and Albright (1990), and our data, one may conclude that:

1. algal growth is initiated in spring with threshold light levels;

2. spring and summer irradiance in the north and south kelp beds are similar to each other and the rest of Puget Sound and;

3. surface irradiance is not limiting by spring months in either the north or south kelp bed.

Effects of sediment flux and associated turbidity and sedimentation of kelp systems have been documented in other regions. Josselyn (1985) found that turbidity was the most limiting factor for macroalgal growth, but not distribution. Dean (1985) found that surface irradiance in *Macrocystis pyrifera* beds varied dramatically with season, but that suspended sediments and their influence on the attenuation of light were of prime importance in determining seasonal patterns of photon flux densities in the nearshore environment. He concluded that surface irradiation levels contributed to the variability in underwater irradiation if viewed on an hourly or daily basis. However the effects of changing surface irradiation on weekly averages of underwater irradiation were overwhelmed by effects of changing water quality due to suspended sediments.

Dean and Deysher (1983) concluded that turbidity from suspended sediments was an important factor defining *Macrocystis pyrifera* sporophyte recruitment during a recruitment window. If irradiance reductions from suspended sediments are severe and chronic, adult *Macrocystis pyrifera* recruitment will be affected. The authors hypothesised that turbidity resulted in kelp bed reductions.

Abrasions and smothering by sediments are also known to be sources of mortality for *M. pyrifera* gametophytes (DeVinney and Volse 1978), but not important for sporophyte production (Dysher and Dean 1986).

In this study, temporary reductions in *N. luetkeana* and *C. costata* densities, and decrease in north bed *Laminaria* sp. density between April and July may have been a result of sub-threshold irradiance that resulted in a delay of sporophyte growth of *N. luetkeana* and *C. costata*, allowing temporary dominance of *Laminaria* sp.

No measurements of turbidity from suspended sediments or sedimentation were made in either kelp bed before, during, or after the slide. It is therefore impossible to quantitatively describe the fate of the sediment in the kelp bed. The large sediment volume introduced into the nearshore habitat immediately following the slide, net northward surface current for this cove, the immediate proximity of the slide to the northern kelp bed, and visual observations of the sediment plume in the north kelp bed area for weeks after the slide, indicate that some portion of the sediment did reach the kelp bed.

The north and south kelp beds are geographically close to each other, have similar irradiance and substrate, and except for spring months, had almost identical algal composition. We therefore conclude that the landslide did not have a major long term effect on the northern kelp bed relative to the southern bed. Instead, the landslide may have resulted in short term differences in dominant brown algae densities in the two beds during spring months immediatly after the landslide. The short term nature of the difference indicates that sediment impacts may have been from temporary turbidity induced lower light levels to sub-threshold levels for sporophyte growth, rather than increased gametophyte or young sporophyte mortality, which would have resulted in long term lowering of plant densities and possibly major shifts in the algal community composition. Instead, densities of the three taxa of kelp, as well as algal percent cover and composition in the two beds, were indistinguishable by summer.

The lack of long term impacts to *N. luetkeana* densities and other brown understory plants is suprising, particularly since the slide occurred during spring months when plants are most vulnerable to sediment impacts. One possible reason for short term impacts may be the resistance of these brown algae to turbidity and sedimentation. Reed (1990), concluded that some kelps may be adapted to seasonal large scale environmental disturbance, and even use such disturbances to trigger pulses of dispersal and settlement. The kelp bed communities of Puget Sound, a fjordal system with steep bluffs and erosion, may be adapted for moderate levels of disturbance from turbidity and sedimentation.

Much more intensive work needs to be done to define factors of sedimentation and nearshore marine and estuarine habitats. In the Pacific Northwest, landslides adjacent to nearshore areas occur frequently, and may be increasing due to human activity such as development and logging. More focus must therefore be put on landslide impacts to nearshore habitats and resources. This study may act as an initial illustration of the complexity of nearshore-upland interactions, and the importance of considering nearshore habitats in upland management practices.

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