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Seasonal Patterns and Controlling Factors of Primary Production in Puget Sound's Central Basin and Possession Sound

Abstract

Primary production was measured using the carbon-14 uptake method in order to assess production and nutrient dynamics in the Central Basin and Possession Sound regions of Puget Sound. Ambient and nutrient-spiked production rates for the entire euphotic zone were determined every 2-6 weeks at four stations from October 1998 through October 2001 (n=42). Nutrient (dissolved nitrogen and phosphate) concentrations, chlorophyll *a*, incident radiation, temperature, and salinity were also measured to examine factors affecting production rates. Seasonal variation in production is well-defined for all four stations, with values integrated over the euphotic zone during summertime (May-September) as high as 13,000 mg C m^{-2} d^{-1}, which drop to less than 100 mg C m^{-2} d^{-1} during wintertime. During the middle of the growing season (April-June) a reduction in production was measured at all stations. Similar variation in biomass, as measured by chlorophyll *a*, was also seen. Considerable interannual variation in production was observed, potentially linked to differences in external physical forcings. Variations in water properties suggest strong oceanic input during 2001. A maximal primary productivity rate was not consistently found at any particular station. Increased primary production due to experimental addition of nutrients was seen at times at all stations during spring and, more often, summer months. Nutrient enhancement of productivity was most evident in Possession Sound. However, based on annual averages, all four stations exhibit substantial production increases in response to added nutrients. Possession Sound and Admiralty Inlet appear to be most susceptible to nutrient limitation towards the tail end of the summer snow melt, when the water column becomes increasingly stratified. Nutrient stimulation was seen at the Admiralty Inlet station during the winter, although light appears to be the primary determinant of production levels during the winter. Consideration of these results along with physical data and modeling will be required to assess regional sensitivity of this part of Puget Sound to nutrient addition.

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Introduction

Human population and land development have dramatically increased in the western Washington area during recent years, presumably leading to additional nutrient input to Puget Sound from both point and non-point sources. This stimulates the need to assess impacts of potential eutrophication in Puget Sound. Eutrophication, or adding excessive nutrients to a basin, can result in phytoplankton growth if, and only if, nutrients are limiting phytoplankton growth. Substantial increases in phytoplankton, in turn, can result in undesirable water quality impacts, such as reduced oxygen concentrations at depth, reduction in water clarity, and possible phytoplankton species shifts.

Historically, Puget Sound has not been viewed as susceptible to eutrophication because of the typically high concentrations of nutrients incoming from the Pacific Ocean, as well as strong mixing in the Main Basin of Puget Sound, which limits exposure of phytoplankton to light and therefore reduces growth. These characteristics of central Puget Sound were responsible for the success of the diversion of sewage from Lake Washington to West Point (Puget Sound) in the late 1950's (Edmondson, 1991). While nutrient loading to Lake Washington caused excessive algal growth, the same loading at West Point did not. Much of the current understanding of Puget Sound phytoplankton dynamics has been based on modeling and measurements of ambient productivity and nutrients at West Point (Winter et al. 1975). However, a much more complex picture is emerging, as a diversity of responses to nutrient addition is apparent both spatially and temporally within greater Puget Sound.

In the early 1980's, Harrison et al. (1983) evaluated the issue of eutrophication in the Strait of Juan de Fuca, Strait of Georgia, and Puget Sound. They judged potential impacts from eutrophication of the Main Basin of Puget Sound to be relatively low. However, they reported that the more poorly flushed bays and inlets of Puget Sound, particularly in the southern end, showed depleted surface nitrate concentrations and very low oxygen concentrations at depth. They assessed that the "early warning signs of eutrophication" were already evident in these poorly flushed bays and inlets of southern Puget Sound.

Bricker et al. (1999) recently reported the overall level of expression of eutrophic conditions to be moderate in (the Main Basin of) Puget Sound and Whidbey Basin and high in Hood Canal and South Puget Sound. The symptoms contributing to eutrophic conditions were chlorophyll *a*, macroalgae, toxic blooms, and, in Hood Canal, low dissolved oxygen. They predicted conditions to worsen, especially in Hood Canal and South Puget Sound, due to increasing population pressures.

Recent studies utilizing nutrient addition experiments on phytoplankton productivity support this conclusion, as data from Budd Inlet (Newton et al., 1998a) and Hood Canal (Newton et al., 1995) show substantially increased rates of primary production upon nutrient addition. However, until now similar studies on nutrient sensitivity of primary production for the Main Basin and nearby Possession Sound have been lacking.

In response to rapid population growth in the Puget Sound region, King County Department of Natural Resources began a siting process in 1999 for a proposed new wastewater treatment plant and marine outfall. The potential for additional nutrient input and subsequent eutrophication effects by this new facility highlighted the need for a study of phytoplankton and nutrient dynamics in the central Puget Sound region.

As part of the siting process, Washington State Department of Ecology was contracted to conduct a joint study with King County Department of Natural Resources to evaluate phytoplankton primary production and nutrient dynamics in Puget Sound's central basin and Possession Sound. This study began in October 1998 and ended in October 2001. Presented herein are results of 36 months of data collection.

Methods

Four stations, located in the central basin of Puget Sound and entrances to Admiralty Inlet and Possession Sound (Figure 1), were sampled every two to six weeks (higher frequency during summer) from October 1998 through October 2001. Stations were chosen to represent the waters of Admiralty Inlet (47 55.04 N, 122 27.97 W), Possession Sound (47 53.51 N, 122 21.41 W), Point Wells, (47 47.12 N, 122 24.40 W) and West Point (47 39.63 N, 122 26.83 W). At each station, we measured primary production (via C-14 uptake), chlorophyll *a* (extracted and *in situ* fluorescence), dissolved nutrients (nitrate, ammonium, nitrite, phosphate, and silicate), phytoplankton species, incident radiation (PAR), temperature, and salinity. Water samples were taken from depths corresponding to the 100, 50, 25, 12, 6, and 1 % surface light intensities, as estimated by secchi depth-derived extinction coefficients, in order to represent the entire euphotic zone (where there is enough light for photosynthesis) at each station. Standard sampling and analytical protocols are described in Newton et al., (1998a) or Newton et al., (1998b).

The standard C-14 uptake experimental protocol was used (Strickland and Parsons, 1968). For the experiments conducted in this study, radioactive C-14 in the form of aqueous sodium bicarbonate was added to the seawater samples, which were then incubated in closed containers for 24 hours at their respective light intensities (simulated by screens in seawater-plumbed deck incubators). During photosynthesis, inorganic carbon, including any from the radioactively labeled bicarbonate, is taken up by phytoplankton and converted to cell biomass. At the end of the incubation, the amount of C-14 that was incorporated into phytoplankton biomass was obtained by filtration of the sample and measurement of the particulate specific activity via liquid scintillation counting. This procedure yields a measure of ambient primary production rates at each depth sampled, which can be integrated over the euphotic zone. In addition, we simulated anthropogenic nutrient loading by adding excess nutrients (30 μM ammonium and 3 μM phosphate) to a duplicate set of experimental samples to determine if there was a change in the production rate due to the increased nutrient concentrations.

Primary production (P), the phytoplankton population growth rate, is the product of the phytoplankton population biomass (B) and the specific growth rate (μ) of the individuals in that population (i.e. normalized to biomass):

$$P = B * \mu$$

We measured chlorophyll *a* integrated through the euphotic zone (mg chl *a* m^{-2}) as an estimate of the water column phytoplankton biomass (B) and integrated primary production (P) via C-14 uptake (mg C m^{-2} d^{-1}). Unfortunately, because the cellular content of chlorophyll is variable, the use of chlorophyll to indicate phytoplankton biomass is an estimate. Thus, with measurements of both P and B, an approximation of specific growth rate (P:B) can be made, however this also will be biased by any variation in the cellular carbon to chlorophyll ratio, which is known to vary with light, nutrients and phytoplankton species.

Results and Discussion

A complete summary of production, nutrient, and chlorophyll data is provided in Appendices 1a-1d. The complete database of all data from the project is housed at both the Washington State Department of Ecology and King County Department of Natural Resources.

Scales of Variation

Spatial

During the growing season (March-September), considerable variation in phytoplankton production was found between the four stations (Figure 2a). A regular pattern in the spatial variation of these measurements was not observed; the location of highest or lowest daily production for any given sampling date was not found consistently at any particular station. Similar results were found for phytoplankton biomass, as indicated by chlorophyll *a* (Figure 2b).

Annual averages of daily production were estimated by multiplying the number of days between sampling dates by the average of the two production rates for those sampling dates, summing these results over the entire year and dividing by 365 days per year. Annual production was found to be highest at West Point in 1999 and 2000 and at Point Wells in 2001 (Table 1). In 1999, production levels were approximately the same at Admiralty Inlet, Possession Sound, and Point Wells. In 2000, the lowest production was found at Possession Sound. In 2001, production levels were approximately the same at Admiralty Inlet, Possession Sound, and West Point and only slightly lower than at Point Wells.

When annual integrated production values were compared to the 3-year mean (Table 2), Point Wells, Admiralty Inlet, and West Point showed lowest production rates in 1999, average rates in 2000 and highest production in 2001. Productivity at Possession Sound followed this same pattern with 1999 low and 2001 high, except that 1999 and 2000 were equally low. This interannual variation will be examined in more detail below. Note that annual production values are not the result of a continuous data set, but are a best estimate from the 12-16 dates that were sampled per year.

To understand how physical processes may influence these patterns we examined the influence of ocean and river forcing on the study area. The majority of the oceanic input into Puget Sound enters at depth through Admiralty Inlet and travels south through the Main Basin. Some of this dense, nutrient-rich water is mixed towards the surface as it comes over the Admiralty Inlet sill

(Cannon, et al., 1990) and mixing also occurs near the south end of the Main Basin, at the Tacoma Narrows sill (Ebbesmeyer and Barnes, 1980). The net outflow from Puget Sound occurs primarily at the surface where fresher, less dense, water flows out of the Main Basin through Admiralty Inlet (Cannon, et al., 1984). Possession Sound, which receives a large percentage of the total freshwater input into Puget Sound, is a more river-dominated system than the Main Basin. Fresh water flows out of Possession Sound at the surface through Admiralty Inlet and, to a lesser extent, through Deception Pass (Cannon, et al., 1990).

Water column stratification was found to vary by region. Figure 3 shows depth at which density (sigma-t) becomes 2 kg/m^3 greater than the density at the surface as an indication of the depth of the mixed layer. The deeper this density occurs, the more well-mixed the water column is. Much of the time the depth of this density gradient is near the surface in Possession Sound, the more river-influenced side-basin of the study area, indicating that the water column is well-stratified year-round. The notable exception to this pattern occurs in the winter of 2001, when the Western Washington area experienced a severe drought. Freshwater input into Possession Sound at this time was considerably lower than other years. This is evident in flow data from the Skagit River (Figure 4), the dominant freshwater input to Puget Sound (the Snohomish River, which also empties into Possession Sound, follows a similar pattern). Diminished fresh water flow likely contributed to the observed decrease in water column stratification (Figure 3).

Point Wells and West Point (average depth 123 and 64m, respectively) appear to follow similar stratification patterns (Figure 3). Both stations are usually well-mixed with the depth at which density is 2 kg/m^3 greater than at the surface usually reaching to the sea floor. In the events where this depth does not reach to the sea floor at one station, it is, with one exception, found at nearly the same depth at the other.

At Admiralty Inlet, most of the time the depth at which density becomes 2 kg/m^3 greater than at the surface reaches all the way to the seabed (average depth of Admiralty Inlet is 119m), as occurs at Point Wells and West Point. During the summertime however, Admiralty Inlet becomes stratified, possibly due to increased freshwater input originating in Possession Sound and flowing out through Admiralty Inlet. Evident in flow data for the Skagit River (Figure 4) is the bimodal pattern of freshwater flow in the area. Flow peaks with winter rains and again in the summer during the snow melt. A similar bimodal pattern in water column stratification was seen at Admiralty Inlet. This pattern suggests that Admiralty Inlet would have a higher likelihood of becoming nutrient limited during the summertime snow melt. Results from the nutrient-added productivity experiments, to be discussed later, confirm a pattern of nutrient limitation occurring at Admiralty Inlet towards the tail end of the summer snow melt (Figure 4).

Seasonal

Consistent with Puget Sound's temperate location, a distinct seasonal pattern in primary production was observed at all stations for all years (Figure 2a). Lower production occurred in winter months with higher levels observed between the months of March to September. This growing season was characterized by a spring bloom, followed by a distinct low in production, then subsequent summer and fall blooms. Phytoplankton biomass, as indicated by chlorophyll *a*, also showed this seasonal trend (Figure 2b). Since phytoplankton populations can change rapidly on a much shorter time scale (days) than we measured, this bi-weekly to monthly view could be missing much in terms of temporal dynamics.

Interannual

Annual integrated daily production (integrated from October to October) was found to be lowest in 1999 (1.9-2.6 g C m^{-2} d^{-1}) and highest in 2001 (3.4-3.7 g C m^{-2} d-^{1}) at all stations (Table 1). In 2000, levels at Point Wells, Admiralty Inlet and West Point (2.7-3.5 g C m^{-2} d^{-1}) were within 8% of each station's 3-year mean, while production at Possession Sound remained as low as in 1999 (2.1 g C m-2 y-1). In order to clarify the possible mechanisms driving this difference, we looked at several factors affecting phytoplankton production. Integrated dissolved inorganic nitrogen (DIN = nitrate + nitrite + ammonium) followed the same pattern as primary production. The interannual chlorophyll pattern did not vary between stations; integrated values were highest in 2001, lowest in 2000 and near the 3-y mean in 1999.

We also examined these patterns in concert with certain physical factors of the greater Puget Sound system that may influence phytoplankton and nutrient dynamics: offshore upwelling of nutrient-rich deep water (Bakun upwelling index, from NOAA; http://www.pfeg.noaa.gov/), local river input (flow data, from USGS; http://water.usgs.gov/wa/nwis/) and local winds (wind speeds, direction, from NDBC; http://seaboard.ndbc.noaa.gov/) – all averaged over the entire year. Results are summarized in Table 2. Sunlight available for photosynthesis, measured either continuously during the growing season or on only the days that were sampled, was not found to vary interannually. Data from NOAA indicate that there was net downwelling in 1999 and 2000 and net upwelling in 2001 (Table 3). During the growing season there were equal amounts of up and downwelling in 1999 and 2000, but net upwelling in 2001. Downwelling occurred every year during winter months (Oct. 1999 to Feb. 2000). Flow data from the Skagit River, which empties into Possession Sound, signifies that the fresh water input into Puget Sound was elevated 17% in 1999, near the 59-y mean in 2000 (+4%), and 36% below average in 2001. During the growing season, winds, which cause mixing of the water column, were strongest in 2001 and weakest in 1999. Stronger wind speeds likely translated to increased mixing of the water column. The effect of winds is not straight forward as winds could cause nutrients to be mixed up towards the surface as well as phytoplankton to be mixed down below the euphotic zone, where light is not available for photosynthesis. Differences in wind direction may also be important: winds in 2001 were found to blow in a northward direction (009˚), whereas in 1999 and 2000 winds were northwestward (328˚ and 322˚).

Some of these trends in external physical forcings are compatible with the observed variation in phytoplankton production, biomass and dissolved nutrients. In 1999 there was net downwelling offshore, which would theoretically limit the supply of nutrient-rich deep water entering Puget Sound through Admiralty Inlet. In addition, the above average river input would tend to stratify the water column, further limiting nutrient availability for phytoplankton production in the euphotic zone. These factors may have caused the lower nutrient concentrations we measured, which may have resulted in the observed lower production levels.

Moderate levels of downwelling and river input, as well as nutrient concentrations and phytoplankton production were recorded at Admiralty Inlet, Point Wells and West Point in 2000; however, nutrients and production were both low at Possession Sound. Possibly, the slightly lower amount of downwelling that occurred offshore this year relative to 1999, coupled with decreased river input, was enough to affect nutrient (and thereby production) levels at the stations in the main basin, but was not strong enough to influence the more river-dominated Possession Sound. Consistent with known circulation patterns (Cannon, et al., 1984; Cannon, et al., 1990; Ebbesmeyer and Cannon, 2001), nutrients mixed to the surface, especially in the southern part of the Main Basin at The Narrows (Ebbesmeyer and Barnes, 1980), might travel back through the Main Basin, where the West Point, Point Wells and Admiralty Inlet stations are located, bypassing the more river-dominated side-basin of Possession Sound. Consistent with this pattern, dissolved nutrient concentrations were regularly found to be lower at Possession Sound than the other stations. The low chlorophyll levels at all stations could be due to mixing, grazing, or other loss factors that were not measured in this study.

Of the 3 years that were sampled, upwelling was greatest and fresh water input was weakest in 2001. A strong oceanic input during 2001 suggests that more nutrient-rich deep water could have entered Puget Sound at depth through Admiralty Inlet, thereby increasing nutrient availability to phytoplankton and supporting high production levels. The lack of fresh water input would also tend to increase nutrient availability by lessening water column stratification, allowing nutrients to be mixed to the surface more easily.

Interannual variations in upwelling may also help to explain why the higher production rates are observed in summer rather than spring months of 2001, as they are in 1999 and 2000. Integrated DIN concentrations (Figure 2c) were generally higher in 2001, possibly due to more frequent intrusions of nutrient-rich upwelled water. Abundant sunlight in summer months coupled with higher than average oceanic input of nutrient-rich deep water could have produced the higher production levels. It is also possible that due to our sampling frequency the height of the spring bloom may have been missed. The strong interannual variation that appears to correlate with differences in ocean and river conditions has implications for assessing the degree of nutrient limitation in future years.

Factors affecting primary production

Correlation of primary production and chlorophyll

If specific growth rates are constant, indicating consistent growth conditions, then chlorophyll and primary production will be well-correlated. During this study, the variation measured in production was found to be only partially correlated with observed variations in chlorophyll (Figure 5). The strength of this correlation was spatially variable; linear regression correlation coefficient r^2 values ranged from 0.58 (Admiralty Inlet) to 0.81 (West Point). This moderate level of coupling between production and chlorophyll at these areas implies that the production per unit chlorophyll is not a constant, that growth conditions, loss processes (grazing, mixing, sinking) or phytoplankton C:chl ratios vary, or a combination of these factors. Chlorophyll (biomass) is sometimes used to indicate primary production when the latter measurements do not exist, although it is well known that many factors can contribute to a non-correlation of these two parameters. Data from this study illustrate that measuring chlorophyll alone is not a precise means of determining phytoplankton production rates in the Puget Sound region.

Seasonal variation in factors affecting primary production

Productivity levels were typically below 100 mg C m^{-2} d^{-1} at all stations during winter months. A strong linear correlation of r^2=0.89 was found between wintertime production and irradiance (Figure 6). This strong correlation indicates that sunlight availability is limiting primary production during winter. This relationship is not found during the spring through fall (Figure 6), implying that other factors are controlling production, such as nutrient availability, grazing losses, or mixing losses.

A shift from low to high primary production and phytoplankton biomass occurred in spring at all four stations (Figure 2a). The P:B ratios also increased from winter (<10mg C mg chl^{-1} d^{-1}) to spring (~40 mg C chl^{-1} d^{-1}). During this time, light becomes more abundant than in winter and nutrient levels in the euphotic zone are high (Figure 2c). The increase in production is likely due to a higher specific growth rate (μ), consistent with an abundance of light and nutrients, and also an accumulation of biomass.

By late spring, light is available but nutrient concentrations drop substantially, especially during 1999 (Figure 2c). Production rates and biomass similarly drop with a lag of approximately one month (Figure 2a,b). The timing of the transition from high to low nutrients and the subsequent spring phytoplankton decline was centered around May in 1999, April in 2000 and March in 2001. Decreased production and biomass could be due to nutrient limitation or result from increased zooplankton grazing and/or losses due to periodic mixing below the euphotic zone.

Production rates and biomass during the summer and fall months were elevated at times, indicating sporadic blooms. This indicates a very dynamic environment in terms of conditions affecting phytoplankton such as light, nutrient availability, mixing, and grazing pressure.

A consistent seasonal pattern in P:B ratios during the phytoplankton growing season was not found. P:B values during 1999 were higher in spring relative to summer, whereas the opposite trend was observed during 2000 and 2001. Values of P:B during summer 2000 and 2001 (except for West Point) were much higher (~70-110 mg C mg chl^{-1} d^{-1}) than the maximum found during 1999 (~50-60 mg C mg chl^{-1} d^{-1}).

Nutrient limitation as a controlling factor of primary production

The focus of this study was to assess the degree that nutrient limitation controls primary production. While this was adequately addressed by nutrient addition experiments, some key rates such as losses of phytoplankton biomass to grazing were not evaluated and may affect interpretation of system dynamics. Losses due to mixing of cells below the euphotic zone, while considered here, should be quantitatively assessed with a coupled hydrodynamic-water quality model.

While the factors controlling primary production are difficult to assess, results of this study show that during the growing season, all stations show large increases in production as a result of added nutrients (by as much as 3 g C m^{-2} d^{-1}), implying some degree of nutrient control is evident at times throughout central Puget Sound (Figure 7). Comparison of the differences in P:B between the spiked and ambient treatments indicates that nutrient limitation affects primary production in central Puget Sound (Table 6). This limitation is evident at all stations during the summer (March to September) and at the Admiralty Inlet station in the winter (October to February). The increase in plankton growth due to the addition of nutrients is more dramatic during the summer months, indicating a more acute nutrient limitation relative to the winter (Figure 8). The strong correlation of production and irradiance strongly suggests that primary production in central Puget Sound is predominately controlled by light availability in winter (Figure 6).

The daily increase in primary productivity due to nutrient addition ranged as high as 77% of the ambient production on a given date (see Appendix 1). While substantial, the overall annual percent increase in production in central Puget Sound and Possession Sound due to nutrient addition was lower than that observed in Budd Inlet (Newton et al., 1998a) and Hood Canal (Newton et al., 1995) where values as high as 83 and 300%, respectively, were measured. Interannual and spatial variation in the strength of the nutrient response is evident. The average net annual increase in production due to addition of nutrient spike for the study area was about 250-350 mg C m^{-2} d^{-1} (Table 4, Figure 7).

In order to assess nutrient sensitivity more quantifiably, we established four thresholds for evaluation (Table 5). We assessed: 1) the number of times that the increase of the nutrient-spiked production was greater than 450 mg C m^{-2} d^{-1} over the ambient production; 2) the number of times that the increase in nutrient-spiked production was 15% or more of the ambient production; 3) the number of times both of these thresholds were exceeded; and 4) the number of times that the DIN decrease over 24 hours was 5 uM more in the spiked treatment than in the ambient treatment, implying greater nutrient uptake. The times when these thresholds were surpassed are summarized in Appendix 2.

Episodes where these four thresholds were surpassed occurred at every station, no less than 10% (Point Wells, threshold 3) and up to 41% (Possession Sound, threshold 4) of the time (Table 5). Possession Sound appears to be consistently the most sensitive area to nutrient addition, judged by all four thresholds. Due to high input of freshwater, this river-dominated side basin is characterized by a more stratified water column. Stronger stratification decreases mixing of nutrients up to the euphotic zone from depth, increasing the possibility of nutrient availability limiting phytoplankton production.

While Possession Sound shows the highest sensitivity to added nutrients, as evident in Table 5 and Figure 7, all stations exhibited nutrient-enhanced production at times. Evaluated relative to thresholds marking extreme responses, Possession Sound stands out. However, based on annual averages of nutrient-spiked production rates, West Point, Admiralty Inlet, and Point Wells all exhibit substantial increases (Table 4). Analyzed by annual averages, the highest increases due to nutrient addition were Possession Sound in 1999, Point Wells in 2000 and West Point in 2001.

Admiralty Inlet, the location of a sill and the entrance to Puget Sound, is generally considered a well-mixed region and was never the station with the highest annual increase in production due to added nutrients. Despite this, substantial levels of nutrient-enhanced production were measured at times each year (Figure 7, Table 4, Table 5). As described earlier, Admiralty Inlet exhibits a bimodal pattern in stratification linked to freshwater flow from winter rains and summer snow melt (Figure 4). Stratification inhibits mixing of nutrient-rich deep water into the euphotic zone. In winter, this is not likely to impact primary production rates since phytoplankton growth is light-limited. However, during the growing season, water column stratification can potentially lead to nutrient limitation. Results of nutrient addition productivity experiments demonstrate a pattern of nutrient limitation occurring towards the tail end of the summer snow melt at Admiralty Inlet (Figure 4). Possession Sound, well-stratified and highly influence by river input, exhibits a similar pattern.

Results from the three years of this study show dynamic spatial and temporal variation in primary production and nutrient response. Despite this variation, enhancement of production from nutrient addition was clearly demonstrated. The analysis presented here relates preliminary findings regarding the association of the nutrient response to variations in water-column physics as well as external forcings.

In order to assess the sensitivity of Puget Sound's central basin and Possession Sound to added nutrients, these results will need to be considered relative to the extensive physical and circulation database generated by the King County Marine Outfall Siting Study as well as be interpreted along with changes in ocean, river and mixing conditions. Variability of zooplankton grazing may also affect system dynamics. Modeling which incorporates all of these parameters should be used to assess impacts on dissolved oxygen concentrations and other trophic levels of the food web. Phytoplankton species samples were taken during this study and preserved for possible future analysis. Though not addressed within the scope of this study, consideration should also be given to potential changes in phytoplankton species composition and succession in response to elevated nutrient concentrations.

Conclusions

Strong spatial and temporal variations in productivity have been observed at all four stations. The magnitude of production was not consistently highest at any particular station, with relative values between the four stations varying on a given day. Distinct seasonal patterns in primary production were discernible though annual rates varied.

Freshwater flow into the Puget Sound system appears to seasonally influence water column stratification and phytoplankton production. A pattern of nutrient limitation was observed at Admiralty Inlet and Possession Sound towards the end of the summer snow melt.

Strong interannual variation was observed and appears to be related to external forcing factors including differences in ocean and river conditions. Comparing the 1999, 2000, and 2001 data we observe that oceanic influence appears to be relatively weak in 1999, moderate in 2000 and stronger in 2001. Such variations must be taken into account when assessing potential impacts to the region of nutrient addition and eutrophication effects.

Despite this interannual variation, increased production due to nutrient addition was seen at all stations every year. All stations combined show nutrient sensitivity, independent of season. Nutrient limitation was most pronounced in Possession Sound, which is consistent with the stronger stratification of this area. Only the Admiralty Inlet station exhibited significant nutrient limitations during the winter months.

Though Possession Sound stands out with regard to extreme events, yearly averages of nutrient enhanced production rates demonstrate that the main basin stations all show evidence of substantial increases and may even dominate in a given year.

An important step to be taken with these data is to determine if increased carbon produced in response to added nutrients is of a magnitude that would significantly affect dissolved oxygen concentrations and/or impact other trophic levels of the food web.

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References

Bricker, S.B., C.G. Clement, D.E. Pirhalla, S.P. Orlando, and D.R.G. Farrow. 1999. National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. NOAA, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science. Silver Spring, MD: 71 pp.

Cannon, G.A., Bretschneider, D.E., and Holbrook, J.R. 1984. Transport variability in a fjord. In: The Estuary as a Filter, V.S. Kennedy (ed.), Academic Press, pp. 67-78.

Cannon, G.A., Holbrook, J.R., and Pashinski, D.J. 1990. Variations in the onset of bottom-water intrusions over the entrance sill of a fjord. Estuaries, 13, 31-42.

Ebbesmeyer, C.C., and Barnes, C.A. 1980. Control of a fjord basin's dynamics by tidal mixing in embracing sill zones. Estuarine and Coastal Marine Science, 11, 311-330.

Ebbesmeyer, C.C., and Cannon, G.A. 2001. Review of Puget Sound Physical Oceanography related to the Triple Junction. Report for King County Department of Natural Resources, 34 pp.

Edmondson, W.T. 1991. The Uses of Ecology: Lake Washington and Beyond. University of Washington Press. 329 p.

Harrison, P.J, D.L. Mackas, B.W. Frost, R.W. Macdonald and E.A. Crecelius. 1994. An assessment of nutrients, plankton and some pollutants in the water column of Juan de Fuca Strait, Strait of Georgia and Puget Sound, and their transboundary transport. Canadian Technical Report of Fisheries and Aquatic Sciences, No. 1948: 138-174.

Newton, J.A., A.L. Thomson, L.B. Eisner, G.A. Hannach, and S.L. Albertson. 1995. Dissolved oxygen concentrations in Hood Canal: Are conditions different than forty years ago? *In* Puget Sound Research '95 Proceedings. Puget Sound Water Quality Authority, Olympia, WA, pp. 1002-1008.

Newton, J.A., M. Edie, and J. Summers. 1998a. Primary productivity in Budd Inlet: Seasonal patterns of variation and controlling factors. *In* Puget Sound Research '98 Proceedings. Puget Sound Action Team, Olympia, WA, pp. 132-151.

Newton, J.A., S.L. Albertson, K. Nakata, and C.L. Clishe. 1998b. Washington State Marine Water Quality in 1996 and 1997. Washington State Department of Ecology, Olympia, WA, Publication No. 98-338.

Strickland, J.D.H. and T.R. Parsons. 1968. A Practical Handbook of Seawater Analysis. Bulletin 167, Fisheries Research Board of Canada, Ottawa.

Winter, D.F., K. Banse, and G.C. Anderson. 1975. The dynamics of phytoplankton blooms in Puget Sound, a fjord in northwestern U.S. Marine Biology, 29: 139-175.

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Tables 1-6

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Table 1. Average daily production (in mg C m-2 d-1) for each station in 1999, 2000, and 2001. Averages are a best estimate from the 12-16 dates that were sampled per year and were seasonally weighted.

	Admiralty Inlet	**Possession Sound**	**Point Wells**	**West Point**
1999	1886	2127	2028	2559
2000	2694	2135	2901	3460
2001	3356	3525	3698	3551
mean	2645	2596	2876	3190

Table 2. Interannual comparison of primary productivity and possible controlling factors. Possession Sound varies from other stations in both production and nutrient levels in 2000.

Admiralty Inlet, Point Wells, West Point						
	Production*	**Integrated DIN***	**Chlorophyll***	**Upwelling**	**River flow#**	**Wind*^**
1999	low	low	average	down	high	low
2000	average	average	low	down	average	average
2001	high	high	high	up	low	high
Possession Sound						
1999	same					
2000	low	low	low	down/up	average	average
2001	same					

*relative to 3-y mean
#relative to 59 and 36-y means for Skagit and Snohomish rivers, respectively
^during growing season (Mar-Sep) only

Table 3. Mean Bakun upwelling indices based on data from http://www.pfeg.noaa.gov/. Units are $m^3 s^{-1}$ 100m of coastline^{-1}. Positive numbers represent offshore transport (upwelling).

	Annual	Growing season (Mar-Sep)	Winter (Oct-Feb)
1999	-42	1	-110
2000	-37	0	-86
2001	6	23	-27
6-y mean	-21	6	-65

Table 4. Annually averaged increases in daily production (in mg C $m^{-2} d^{-1}$) due to nutrient addition.

	Admiralty Inlet	Possession Sound	Point Wells	West Point	average
1999	360	405	320	292	344
2000	173	292	334	236	259
2001	376	314	209	552	363

Table 5. Increases in production due to nutrient addition. Percentage of times threshold was surpassed at each station, out of a total of 42 sampling dates. Possession Sound stands out as being the most sensitive to added nutrients.

#	Threshold	Admiralty Inlet	Possession Sound	Point Wells	West Point
1	increased production, by wt *(>450 mg C m^{-2} d^{-1})*	24%	33%	19%	31%
2	increased production, by % *(>15%)*	19%	36%	24%	29%
3	increased production, by wt and % *(>450 mg C m^{-2} d^{-1}* AND *>15%)*	12%	24%	10%	19%
4	increased nutrient utilization *(spike>ambient+5uM)*	21%	41%	24%	21%

Table 6. P:B of ambient and spiked samples.

	P:B, Ambient Sample (mean)	P:B Spiked Sample (mean)	Significant Increase in Spiked P:B[a]
All Stations			
Summer	46.0	50.5	Yes
Winter	16.5	17.6	Yes
Admiralty Inlet			
Summer	51.1	55.5	Yes
Winter	15.3	16.3	Yes
Point Wells			
Summer	44.6	48.7	Yes
Winter	15.6	16.3	No
Possession Sound			
Summer	49.7	56.1	Yes
Winter	21.1	22.7	No
West Point			
Summer	39.1	42.2	Yes
Winter	13.3	14.4	No

[a] Non-parametric sign test, p=0.05

Figures 1-8

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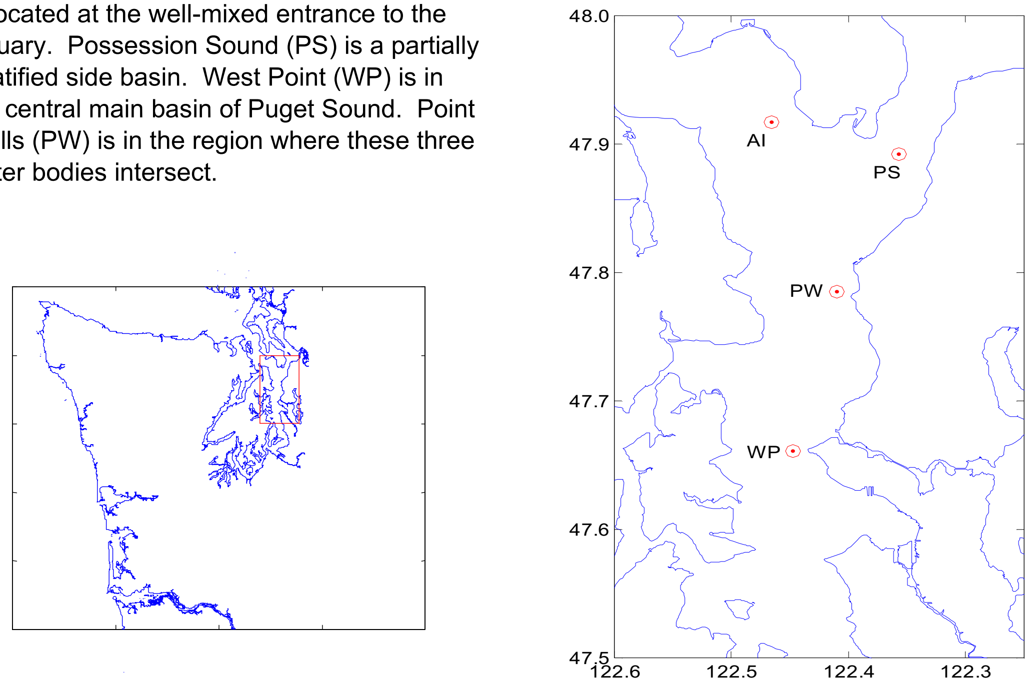
Figure 1. Area of study. Admiralty Inlet (AI) is located at the well-mixed entrance to the estuary. Possession Sound (PS) is a partially stratified side basin. West Point (WP) is in the central main basin of Puget Sound. Point Wells (PW) is in the region where these three water bodies intersect.



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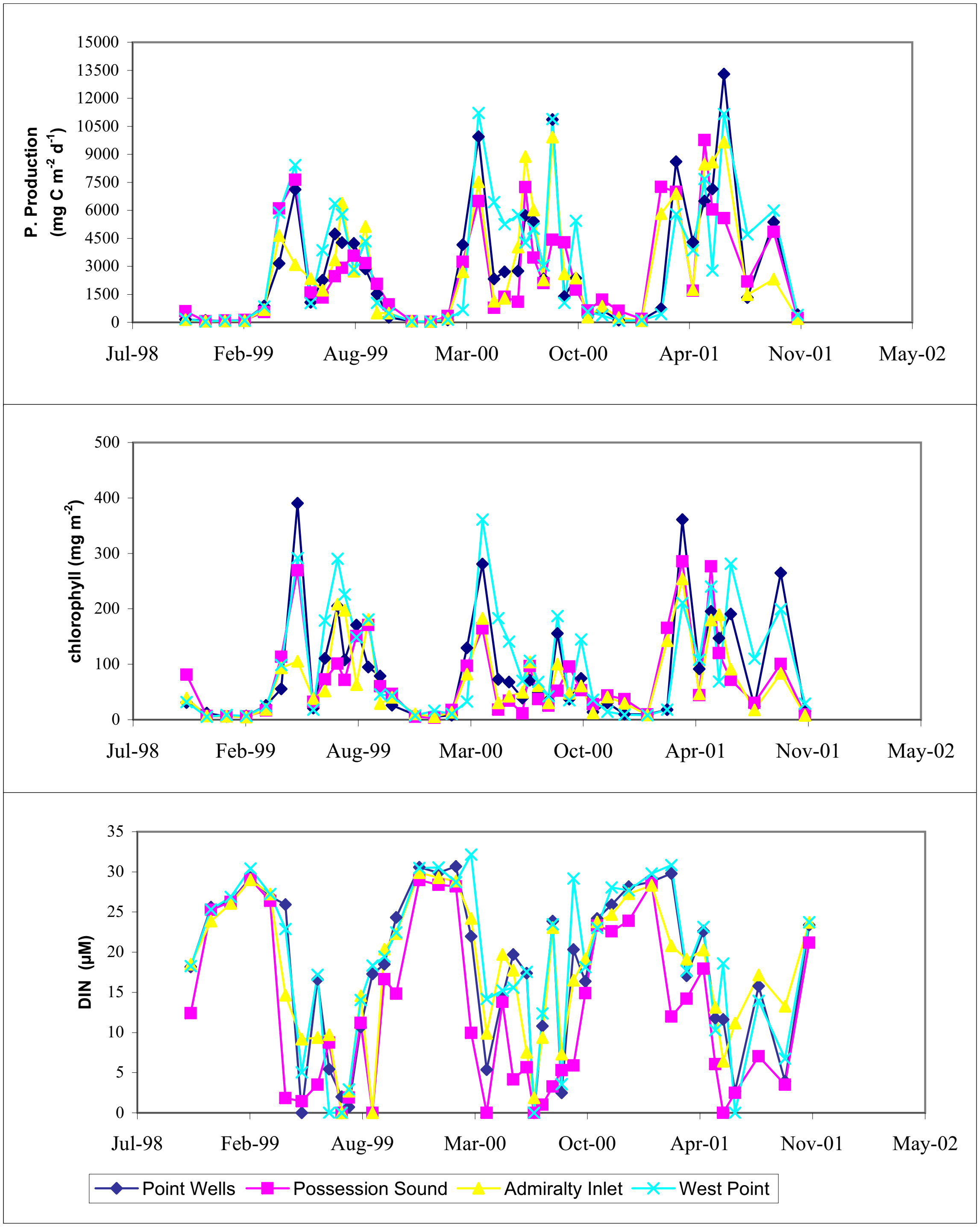

Figure 2. Seasonal pattern of (a) primary production, (b) phytoplankton biomass, as indicated by chlorophyll a, and (c) surface DIN for each station for three years. Production and chlorophyll values are integrated over the euphotic zone.

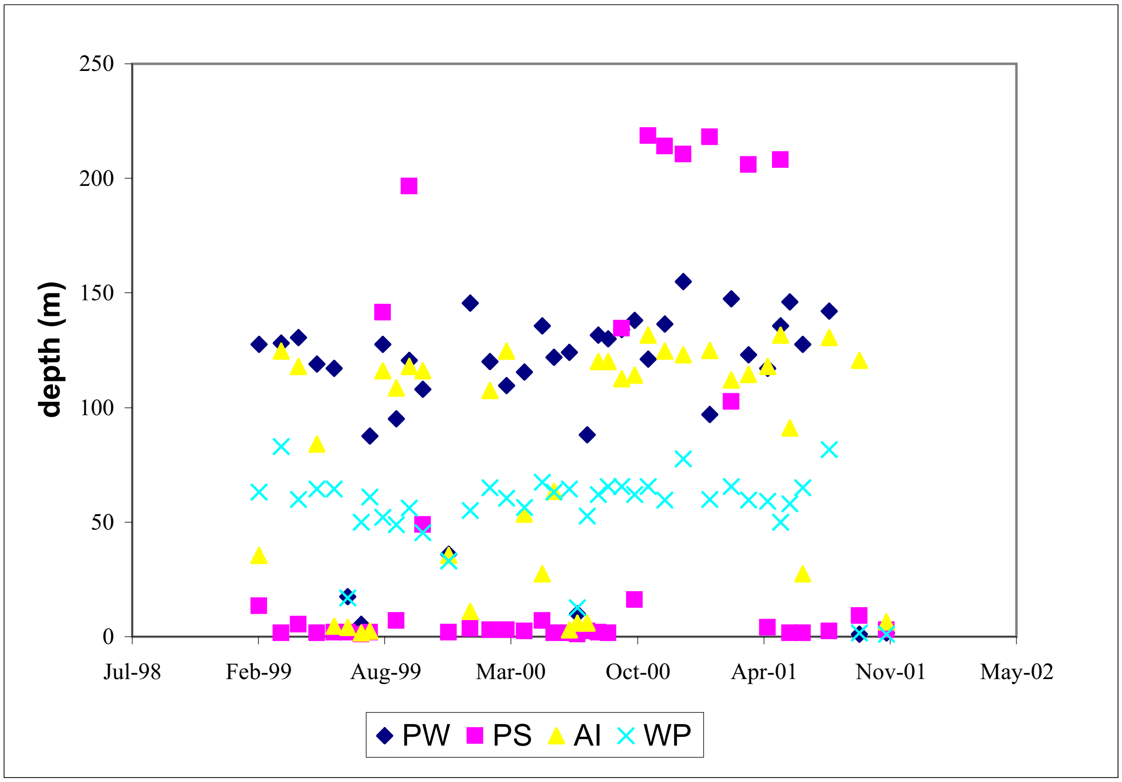

Figure 3. Depth where sigma-t becomes 2 kg/m^3 greater than at the surface. Average water column depth of PW=123m, PS=205m, AI=119m, and WP=64m.

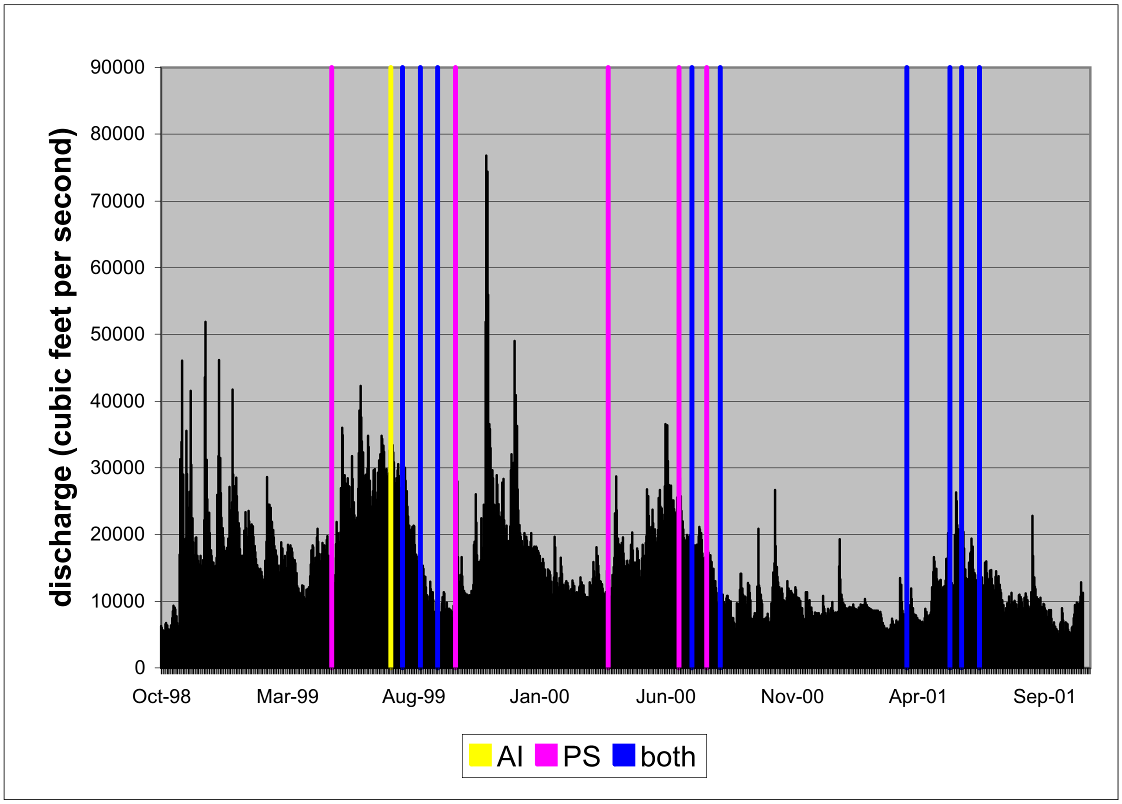

Figure 4. Flow data for Skagit River. Also shown are dates that phytoplankton production increased by more than 450 mg C m^{-2} d^{-1} at Admiralty Inlet and Possession Sound with addition of nutrient spike.

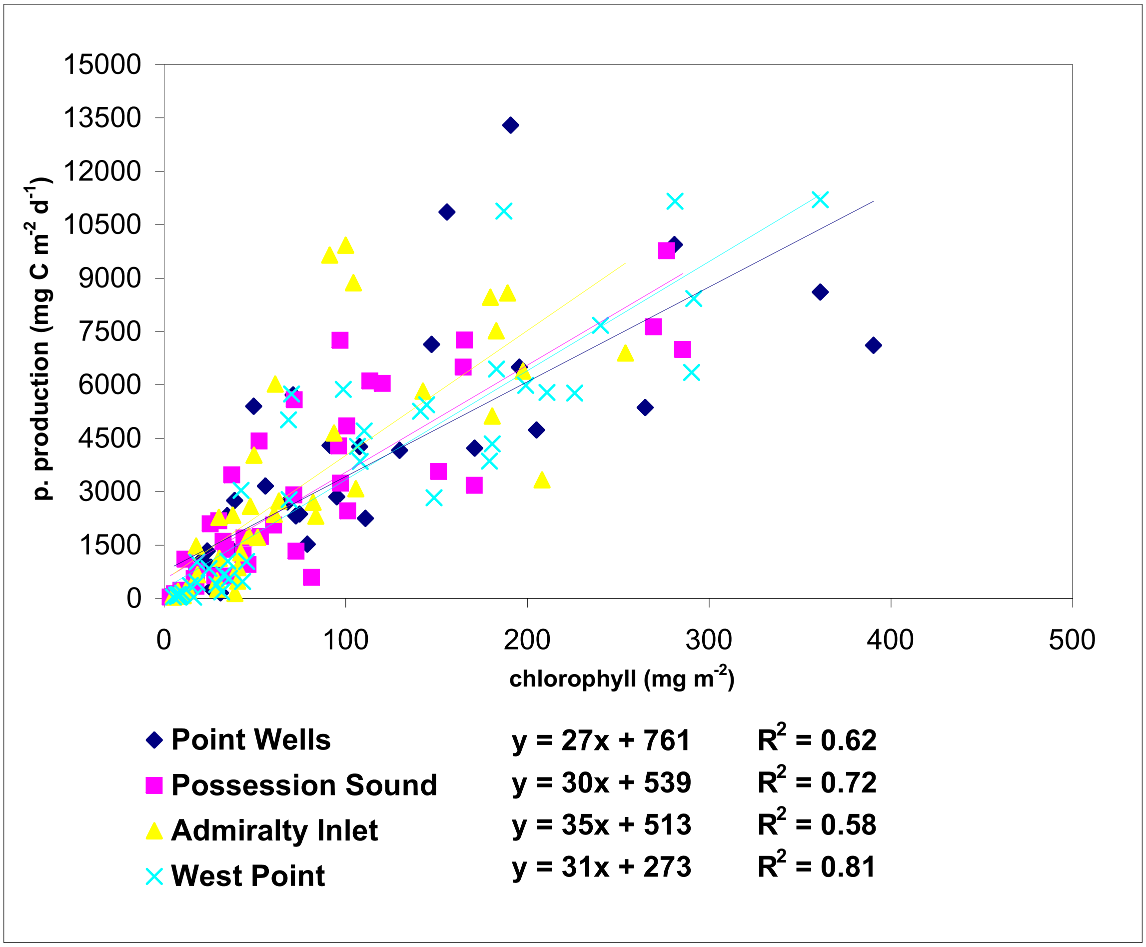

Figure 5. Correlation of primary production and phytoplankton biomass (chlorophyll *a*). Values are integrated over the euphotic zone.

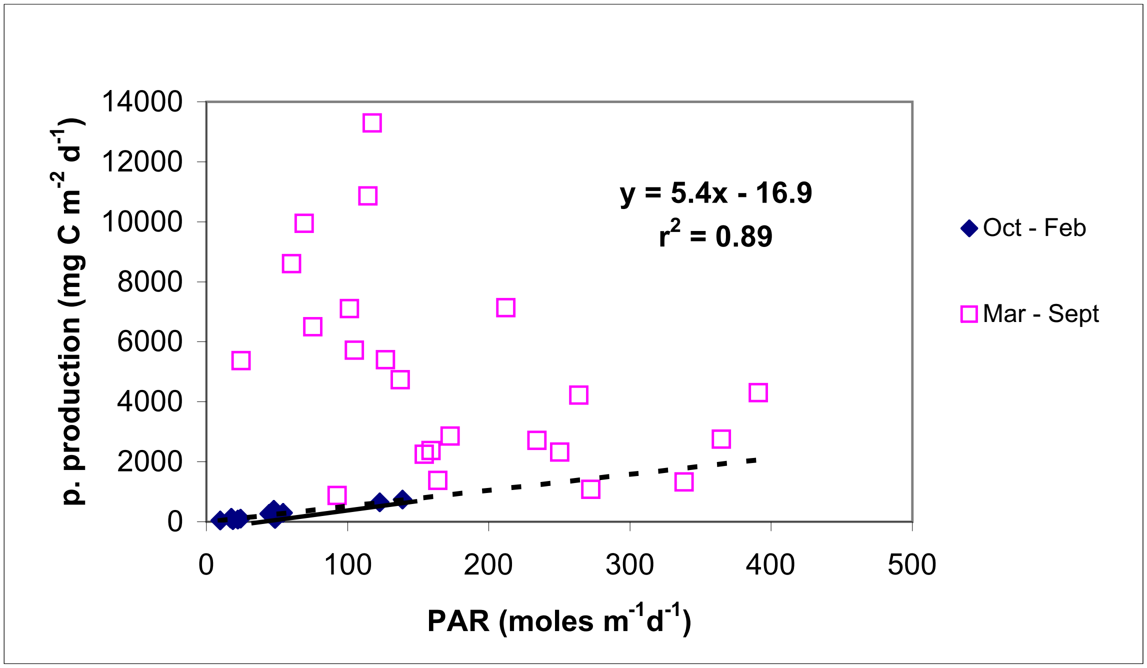

Figure 6. Correlation of integrated primary production with water column irradiance for duration of study at Point Wells.

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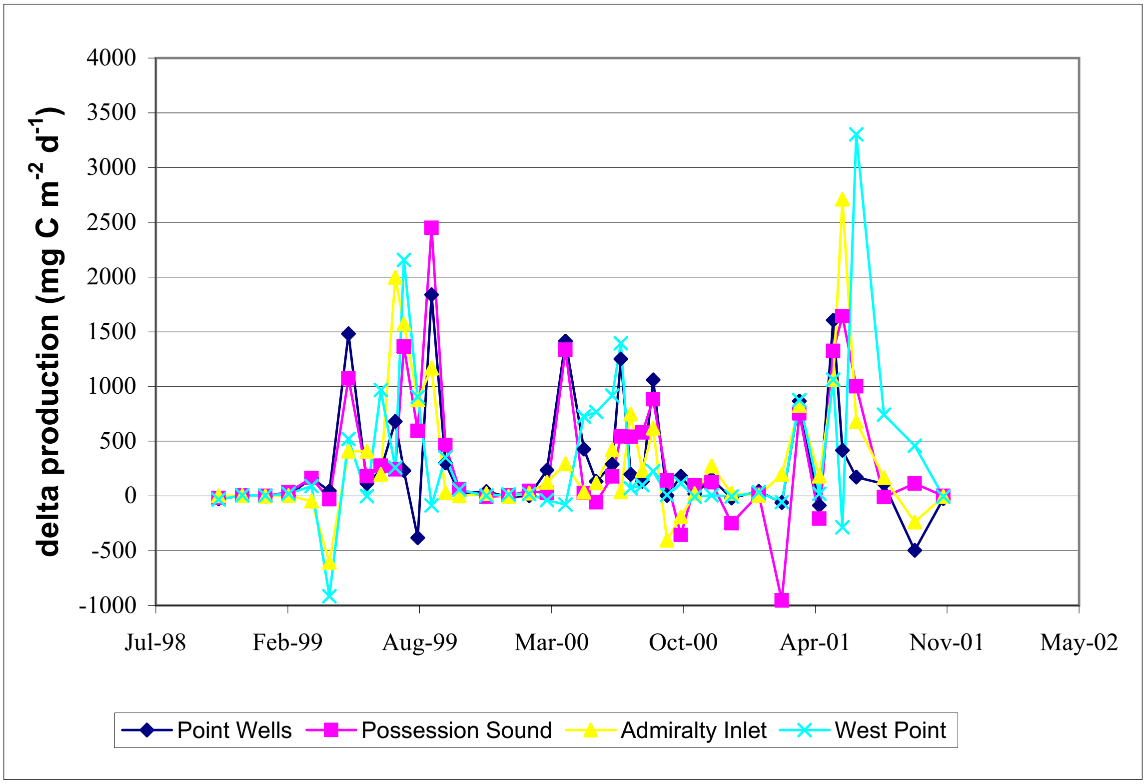

Figure 7. Increase in production (by weight) due to the addition of nutrient spike.

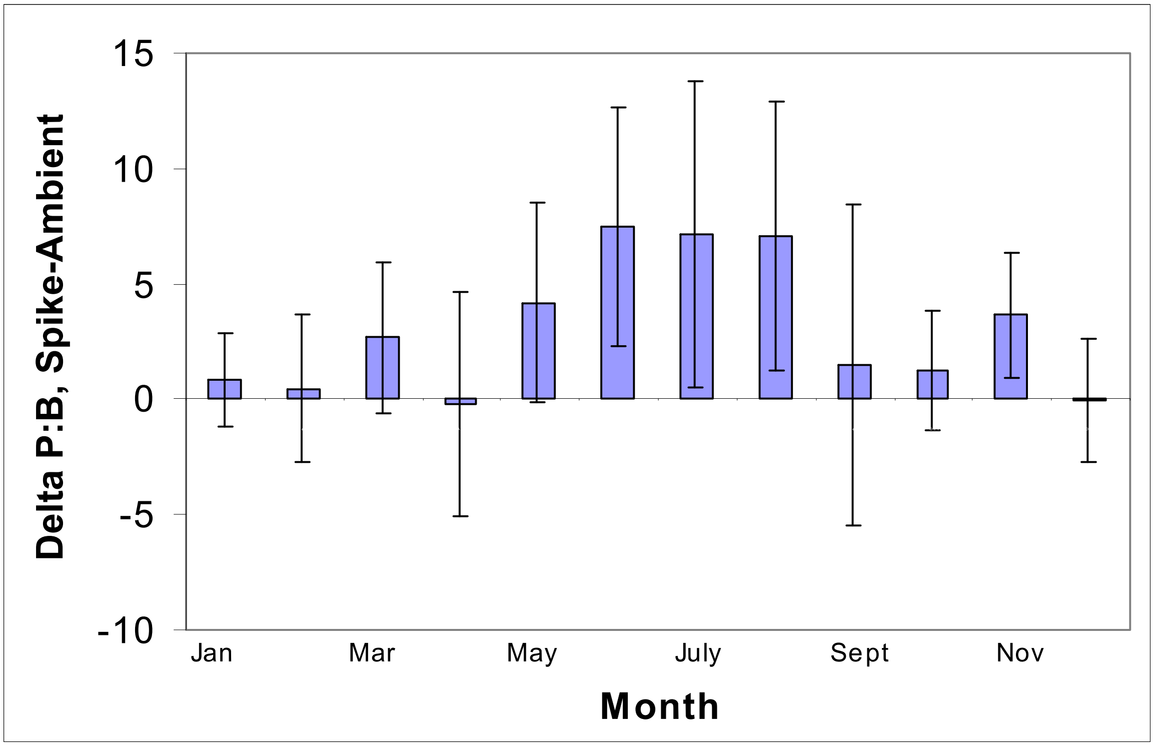

Figure 8. Difference in P:B between ambient and spike samples for all sites combined.

Appendices

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Appendix 1a. Production, nutrient and chlorophyll data for all experiments at Admiralty Inlet. Integrated values are integrated over the euphotic zone.

Exp #	Date	Euphotic zone (m)	Incident radiation (moles m^{-2} d^{-1})	Integrated DIN (mmoles m^{-2})	Surface DIN (uM)	Integrated p.prod. ambient (mg C m^{-2} d^{-1})	Integrated p.prod. spike (mg C m^{-2} d^{-1})	Delta production (mg C m^{-2} d^{-1})	% change	Integrated chl (mg chl m^{-2})	P:B (μ) ambient (mg C mg chl^{-1} d^{-1})	P:B (μ) spike (mg C mg chl^{-1} d^{-1})
1	27-Oct-98	35.1	n/a	695	18	140	141	1	1	39.0	4	4
2	2-Dec-98	24.2	5	575	24	61	64	3	5	6.6	9	10
3	6-Jan-99	17.4	8	440	26	75	73	-3	-4	6.1	12	12
4	10-Feb-99	15.1	11	432	29	80	84	5	6	5.0	16	17
5	17-Mar-99	19.5	17	525	27	670	622	-48	-7	18.3	37	34
6	13-Apr-99	28.9	n/a	690	15	4643	4036	-608	-13	93.5	50	43
7	12-May-99	17.7	35	331	9	3081	3490	408	13	105.5	29	33
8	9-Jun-99	25.2	46	436	9	2333	2741	408	17	37.7	62	73
9	30-Jun-99	31.5	21	575	10	1714	1912	199	12	51.6	33	37
10	22-Jul-99	15.3	35	94	0	3332	5328	1996	60	208.1	16	26
11	4-Aug-99	17.9	n/a	147	3	6387	7958	1571	25	197.4	32	40
12	25-Aug-99	19.2	45	344	15	2734	3612	878	32	63.1	43	57
13	15-Sep-99	7.5	25	21	0	5122	6288	1166	23	180.5	28	35
14	6-Oct-99	29.4	n/a	613	20	494	523	28	6	29.1	17	18
15	27-Oct-99	30.9	6	706	22	487	488	1	0	40.6	12	12
16	7-Dec-99	28.6	3	804	30	75	96	22	29	10.4	7	9
17	10-Jan-00	11.7	2	331	29	37	33	-5	-13	5.4	7	6
18	10-Feb-00	22.1	9	678	29	208	233	25	12	13.5	15	17
19	8-Mar-00	22.9	n/a	570	24	2703	2826	123	5	81.9	33	34
20	5-Apr-00	13.0	25	215	10	7520	7813	293	4	182.7	41	43
21	3-May-00	26.0	43	508	20	1128	1161	33	3	30.3	37	38
22	22-May-00	22.1	43	461	18	1276	1396	119	9	42.2	30	33
23	15-Jun-00	11.4	56	152	8	4025	4448	423	11	49.5	81	90
24	28-Jun-00	7.8	47	63	2	8867	8904	38	0	104.1	85	86
25	13-Jul-00	12.7	50	191	9	6018	6765	747	12	61.1	98	111
26	31-Jul-00	26.0	n/a	535	23	2274	2505	231	10	30.2	75	83
27	16-Aug-00	15.1	46	211	7	9921	10541	620	6	100.0	99	105
28	6-Sep-00	20.5	20	451	17	2588	2184	-404	-16	47.4	55	46
29	27-Sep-00	28.3	22	561	19	2364	2175	-189	-8	60.6	39	36
30	18-Oct-00	25.7	7	631	24	282	303	21	8	12.5	23	24
31	13-Nov-00	41.6	12	1058	25	864	1137	273	32	40.6	21	28
32	13-Dec-00	30.9	2	832	27	257	281	24	9	29.5	9	10
33	23-Jan-01	20.8	3	609	28	86	88	3	3.079007	8	10.09447398	10.40528357
34	27-Feb-01	23.4	20	585	21	5818	6015	197	3.381252	142	40.86580499	42.24758063
35	26-Mar-01	25.5	13	583	19	6892	7716	824	11.9	254	27.1	30.4
36	25-Apr-01	31.2	39	764	20	1753	1933	180	10.26054	47	37.67465452	41.54027662
37	16-May-01	13.0	23	215	13	8458	9518	1059	12.52516	180	47.10023008	52.99960748
38	30-May-01	14.3	48	120	6	8580	11289	2709	31.56946	189	45.38884489	59.71785749
39	20-Jun-01	10.9	50	199	11	9642	10320	678	7.034686	91	105.8333599	113.2784045
40	1-Aug-01	27.6	43	509	17	1474	1641	167	11.33817	18	83.29823831	92.74273509
41	17-Sep-01	20.5	8	351	13	2306	2068	-238	-10.33086	83	27.62865846	24.77437989
42	30-Oct-01	26.0	6	634	24	200	194	-6	-3.073889	8	26.3486661	25.53873739

Appendix 1b. Primary production, nutrient and chlorophyll data for all experiments at Point Wells. Integrated values are integrated over the euphotic zone.

Exp #	Date	Euphotic zone (m)	Incident radiation (moles m^{-2} d^{-1})	Integrated DIN (mmoles m^{-2})	Surface DIN (uM)	Integrated p.prod. ambient (mg C m^{-2} d^{-1})	Integrated p.prod. spike (mg C m^{-2} d^{-1})	Delta production (mg C m^{-2} d^{-1})	% change	Integrated chl (mg chl m^{-2})	P:B (μ) ambient (mg C mg chl^{-1} d^{-1})	P:B (μ) spike (mg C mg chl^{-1} d^{-1})
1	27-Oct-98	32.5	n/a	659	18	158	132	-26	-17	31.0	5	4
2	2-Dec-98	19.5	5	479	26	103	106	3	3	11.6	9	9
3	6-Jan-99	11.7	8	313	26	73	69	-3	-4	5.7	13	12
4	10-Feb-99	17.7	11	516	29	94	97	3	3	6.4	15	15
5	17-Mar-99	22.4	17	611	27	870	1034	164	19	25.7	34	40
6	13-Apr-99	30.4	n/a	780	26	3161	3205	44	1	55.7	57	58
7	12-May-99	11.7	35	26	0	7107	8590	1483	21	390.4	18	22
8	9-Jun-99	24.4	46	401	17	1077	1191	114	11	20.7	52	57
9	30-Jun-99	29.9	21	456	5	2253	2489	236	10	110.7	20	22
10	22-Jul-99	15.9	35	176	2	4733	5413	680	14	205.0	23	26
11	4-Aug-99	10.9	n/a	102	1	4267	4498	231	5	107.5	40	42
12	25-Aug-99	24.2	45	313	11	4219	3837	-382	-9	171.0	25	22
13	15-Sep-99	28.1	25	542	17	2853	4693	1840	64	95.0	30	49
14	6-Oct-99	25.5	n/a	495	18	1524	1823	300	20	78.8	19	23
15	27-Oct-99	32.2	6	749	24	270	295	25	9	26.1	10	11
16	7-Dec-99	26.0	3	703	31	56	96	41	73	8.4	7	11
17	10-Jan-00	22.1	2	648	30	40	33	-7	-16	5.4	7	6
18	10-Feb-00	22.1	9	680	31	121	121	-1	0	8.2	15	15
19	8-Mar-00	26.5	n/a	671	22	4157	4395	237	6	129.6	32	34
20	5-Apr-00	11.4	25	141	5	9942	11356	1414	14	280.8	35	40
21	3-May-00	23.9	43	419	14	2318	2745	427	18	72.5	32	38
22	22-May-00	22.1	43	461	20	2711	2844	133	5	67.9	40	42
23	15-Jun-00	26.8	56	499	17	2752	3043	291	11	38.8	71	78
24	28-Jun-00	9.1	47	76	0	5719	6969	1251	22	70.9	81	98
25	13-Jul-00	10.4	50	142	11	5402	5600	198	4	49.3	109	114
26	31-Jul-00	32.0	n/a	632	24	2323	2456	133	6	34.7	67	71
27	16-Aug-00	10.1	46	103	2	10856	11916	1060	10	155.6	70	77
28	6-Sep-00	33.8	20	752	20	1376	1379	3	0	37.2	37	37
29	27-Sep-00	30.2	22	573	16	2373	2554	181	8	74.5	32	34
30	18-Oct-00	31.2	7	737	24	294	315	21	7	13.6	22	23
31	13-Nov-00	42.1	12	1087	26	645	799	154	24	30.2	21	26
32	13-Dec-00	31.2	2	845	28	107	89	-19	-18	10.0	11	9
33	23-Jan-01	20.8	3	592	29	131	175	44	34	9	14	19
34	27-Feb-01	28.6	20	850	30	735	673	-62	-8	18	40	37
35	26-Mar-01	18.5	13	322	17	8605	9472	867	10	361	24	26
36	25-Apr-01	40.8	39	918	23	4298	4211	-87	-2	91	47	46
37	16-May-01	13.3	23	209	12	6496	8102	1606	25	196	33	41
38	30-May-01	17.9	48	250	12	7136	7552	416	6	147	49	51
39	20-Jun-01	9.6	50	79	3	13295	13466	171	1	191	70	71
40	1-Aug-01	32.5	43	595	16	1329	1438	109	8	24	56	61
41	17-Sep-01	12.5	8	88	4	5367	4870	-497	-9	265	20	18
42	30-Oct-01	31.2	6	742	23	402	376	-25	-6	15	26	25

Appendix 1c. Production, nutrient and chlorophyll data for all experiments at Possession Sound. Integrated values are integrated over the euphotic zone.

Exp #	Date	Euphotic zone (m)	Incident radiation (moles m^{-2} d^{-1})	Integrated DIN (mmoles m^{-2})	Surface DIN (uM)	Integrated p.prod. ambient (mg C m^{-2} d^{-1})	Integrated p.prod. spike (mg C m^{-2} d^{-1})	Delta production (mg C m^{-2} d^{-1})	% change	Integrated chl (mg chl m^{-2})	P:B (μ) ambient (mg C mg chl^{-1} d^{-1})	P:B (μ) spike (mg C mg chl^{-1} d^{-1})
1	27-Oct-98	24.7	n/a	450	12	585	565	-20	-3	81.1	7	7
2	2-Dec-98	14.3	5	349	25	61	66	4	7	6.8	9	10
3	6-Jan-99	14.3	8	378	26	93	95	2	2	5.8	16	16
4	10-Feb-99	14.6	11	422	29	128	164	35	27	5.8	22	28
5	17-Mar-99	14.8	17	402	26	555	720	165	30	16.6	34	44
6	13-Apr-99	18.2	n/a	363	2	6105	6075	-30	0	113.3	54	54
7	12-May-99	19.2	35	176	1	7631	8707	1076	14	269.4	28	32
8	9-Jun-99	17.4	46	240	3	1597	1779	182	11	32.5	49	55
9	30-Jun-99	21.3	21	319	9	1321	1598	276	21	72.6	18	22
10	22-Jul-99	12.2	35	126	0	2461	2704	243	10	101.1	24	27
11	4-Aug-99	16.1	n/a	160	2	2909	4273	1364	47	71.5	41	60
12	25-Aug-99	23.7	45	284	11	3567	4159	592	17	151.1	24	28
13	15-Sep-99	7.3	25	27	0	3174	5621	2447	77	170.7	19	33
14	6-Oct-99	29.9	n/a	608	17	2056	2520	464	23	60.3	34	42
15	27-Oct-99	18.2	6	390	15	951	1013	62	7	46.3	21	22
16	7-Dec-99	8.3	3	227	29	54	46	-8	-14	5.1	11	9
17	10-Jan-00	10.9	2	305	28	31	34	3	9	3.3	9	10
18	10-Feb-00	20.8	9	613	28	336	382	46	14	17.7	19	22
19	8-Mar-00	12.7	n/a	282	10	3234	3261	27	1	97.0	33	34
20	5-Apr-00	9.4	25	127	0	6492	7828	1336	21	164.6	39	48
21	3-May-00	25.0	43	526	14	770	795	25	3	17.8	43	45
22	22-May-00	20.8	43	422	4	1372	1313	-60	-4	34.0	40	39
23	15-Jun-00	7.0	56	106	6	1095	1272	177	16	11.6	94	110
24	28-Jun-00	9.1	47	79	0	7245	7787	542	7	96.9	75	80
25	13-Jul-00	8.1	50	104	1	3469	4010	541	16	37.2	93	108
26	31-Jul-00	18.5	n/a	341	3	2097	2677	579	28	25.4	83	106
27	16-Aug-00	10.4	46	143	5	4424	5306	882	20	52.4	84	101
28	6-Sep-00	10.1	20	153	6	4279	4420	141	3	96.0	45	46
29	27-Sep-00	18.2	22	388	15	1740	1382	-358	-21	53.1	33	26
30	18-Oct-00	39.5	7	948	23	633	729	96	15	27.9	23	26
31	13-Nov-00	30.2	12	761	23	1213	1337	124	10	43.6	28	31
32	13-Dec-00	29.9	2	794	24	619	370	-249	-40	36.9	17	10
33	23-Jan-01	18.2	3	522	29	179	194	15	8	9	19	21
34	27-Feb-01	13.3	20	291	12	7254	6299	-956	-13	165	44	38
35	26-Mar-01	15.6	13	289	14	6990	7745	755	11	285	24	27
36	25-Apr-01	24.4	39	547	18	1692	1486	-206	-12	44	38	34
37	16-May-01	10.7	23	83	6	9766	11089	1323	14	277	35	40
38	30-May-01	9.9	48	71	0	6042	7684	1642	27	120	50	64
39	20-Jun-01	7.5	50	105	2	5579	6581	1002	18	72	78	92
40	1-Aug-01	28.3	43	479	7	2181	2170	-11	-1	30	72	72
41	17-Sep-01	15.1	8	187	3	4845	4959	114	2	101	48	49
42	30-Oct-01	20.8	6	491	21	227	226	-1	0	9	24	24

Appendix 1d. Production, nutrient and chlorophyll data for all experiments at West Point. Integrated values are integrated over the euphotic zone.

Exp #	Date	Euphotic zone (m)	Incident radiation (moles m^{-2} d^{-1})	Integrated DIN (mmoles m^{-2})	Surface DIN (uM)	Integrated p.prod. ambient (mg C m^{-2} d^{-1})	Integrated p.prod. spike (mg C m^{-2} d^{-1})	Delta production (mg C m^{-2} d^{-1})	% change	Integrated chl (mg chl m^{-2})	P:B (μ) ambient (mg C mg chl^{-1} d^{-1})	P:B (μ) spike (mg C mg chl^{-1} d^{-1})
1	27-Oct-98	32.5	n/a	649	18	185	153	-32	-17	31.7	6	5
2	2-Dec-98	9.1	5	234	25	45	51	6	14	5.0	9	10
3	6-Jan-99	10.4	8	276	27	93	96	4	4	8.7	11	11
4	10-Feb-99	15.6	11	457	30	93	112	19	20	6.8	14	16
5	17-Mar-99	20.5	17	557	27	842	933	91	11	24.7	34	38
6	13-Apr-99	29.4	n/a	751	23	5873	4959	-915	-16	98.6	60	50
7	12-May-99	13.8	35	130	5	8428	8949	521	6	291.5	29	31
8	9-Jun-99	32.2	46	597	17	1022	1020	-2	0	18.1	56	56
9	30-Jun-99	22.9	21	209	0	3861	4829	969	25	179.1	22	27
10	22-Jul-99	16.9	35	206	0	6345	6604	259	4	290.3	22	23
11	4-Aug-99	16.9	n/a	132	3	5769	7926	2157	37	225.9	26	35
12	25-Aug-99	28.9	45	417	14	2828	3734	907	32	148.5	19	25
13	15-Sep-99	27.8	25	498	18	4345	4257	-87	-2	180.5	24	24
14	6-Oct-99	38.7	n/a	822	19	1040	1393	353	34	45.3	23	31
15	27-Oct-99	26.8	6	641	22	479	537	57	12	43.1	11	12
16	7-Dec-99	27.0	3	733	30	55	59	4	8	7.5	7	8
17	10-Jan-00	19.2	2	566	31	34	48	14	41	16.3	2	3
18	10-Feb-00	19.5	9	593	29	148	166	18	13	10.2	14	16
19	8-Mar-00	26.3	n/a	918	32	670	635	-34	-5	32.8	20	19
20	5-Apr-00	12.7	25	147	14	11308	11083	-225	-2	361.1	31	31
21	3-May-00	24.2	43	422	15	6408	7135	727	11	183.0	35	39
22	22-May-00	16.9	43	299	16	5255	6034	780	15	141.1	37	43
23	15-Jun-00	19.8	56	475	18	5725	6598	873	15	70.1	82	94
24	28-Jun-00	9.1	47	11	0	4221	5570	1348	32	106.4	40	52
25	13-Jul-00	15.6	50	262	12	5083	5196	113	2	68.4	74	76
26	31-Jul-00	25.7	n/a	508	23	3040	3139	99	3	42.3	72	74
27	16-Aug-00	13.5	46	179	4	10780	11221	441	4	187.0	58	60
28	6-Sep-00	26.8	20	871	29	1027	1042	15	1	35.0	29	30
29	27-Sep-00	27.3	22	525	18	5430	5554	124	2	144.5	38	38
30	18-Oct-00	45.5	7	1165	23	565	555	-9	-2	35.8	16	15
31	13-Nov-00	31.2	12	876	28	363	368	5	1	14.4	25	26
32	13-Dec-00	28.1	2	770	28	87	81	-6	-6	9.0	10	9
33	23-Jan-01	20.8	3	609	30	116	150	34	29	8	15	19
34	27-Feb-01	23.9	20	735	31	440	384	-56	-13	18	24	21
35	26-Mar-01	18.5	13	431	18	5788	6664	875	15	211	27	32
36	25-Apr-01	35.1	39	818	23	3854	3873	20	1	108	36	36
37	16-May-01	13.5	23	146	10	7676	8738	1062	14	240	32	36
38	30-May-01	20.5	48	516	19	2781	2495	-286	-10	69	40	36
39	20-Jun-01	7.8	50	0	0	11160	14463	3302	30	281	40	51
40	1-Aug-01	22.9	43	372	14	4705	5448	743	16	110	43	49
41	17-Sep-01	16.9	8	217	7	5987	6447	460	8	199	30	32
42	30-Oct-01	27.3	6	700	24	392	387	-5	-1	29	14	13

Appendix 2. Times when thresholds to assess nutrient sensitivity were surpassed.

1) Increased Production (>450 mg C m^{-2} d^{-1}):

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Admiralty Inlet	1998												
	1999							x	xx	x			
	2000							x	x				
	2001			x		xx	x						
Possession Sound	1998												
	1999					x			xx	x	x		
	2000				x		x	xx	x				
	2001			x		xx	x						
Point Wells	1998												
	1999					x		x		x			
	2000				x		x		x				
	2001			x		x							
West Point	1998												
	1999					x	x		xx				
	2000					xx	xx						
	2001			x		x	x		x	x			

2) Increased Production (>15%):

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Admiralty Inlet	1998												
	1999						x	x	xx	x			x
	2000											x	
	2001					x							
Possession Sound	1998												
	1999		x	x			x		xx	x	x		
	2000				x		x	xx	xx		x		
	2001					x	x						
Point Wells	1998												
	1999			x		x				x	x		x
	2000					x	x					x	
	2001	x				x							
West Point	1998												
	1999		x				x		xx		x		
	2000	x					xx						
	2001	x		x			x		x				

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Appendix 2(cont). Times when thresholds to assess nutrient sensitivity were surpassed.

3) Increased Production (>450 mg C m^{-2} d^{-1} and >15%):

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Admiralty Inlet	1998												
	1999							x	xx	x			
	2000												
	2001					x							
Possession Sound	1998												
	1999								xx	x	x		
	2000				x			xx	x				
	2001					x	x						
Point Wells	1998												
	1999					x				x			
	2000						x						
	2001					x							
West Point	1998												
	1999						x		xx				
	2000						xx						
	2001			x			x		x				

4) Increased Nutrient Utilization (spike>ambient+5uM):

Site	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Admiralty Inlet	1998												
	1999						x		x	x			
	2000						x	x	x				
	2001			x		x	x						
Possession Sound	1998												x
	1999				x	x	x	x	x	x			
	2000				x		x	xx	x			x	
	2001					xx	x			x			
Point Wells	1998												
	1999					x		x	x				
	2000				x		x	x	x				
	2001			x	x		x						
West Point	1998												x
	1999					x	x	x	x				
	2000						x	x	x				
	2001						x						

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec