Significant changes in macronutrient composition along the urban corridor of Puget Sound from 1998-2008

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Urbanization

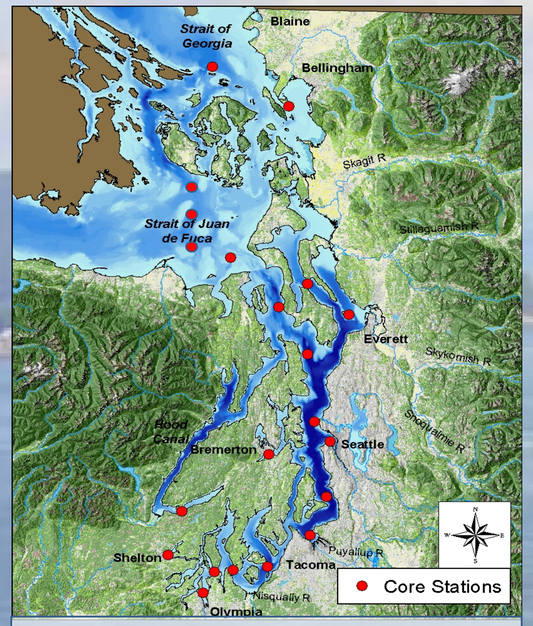

Fig. 1 **Monitoring stations in Puget Sound**

Introduction

Puget Sound (Fig. 1) is a complex fjord-type estuary in Washington State, significantly influenced by patterns of **oceanic variability.** It is a large **urban and industrial corridor** expected to reach a population density of **3.6 million by 2020** (Fig. 2).

Many factors affect water quality in Puget Sound including terrestrial, oceanographic (Fig. 3) and anthropogenic processes. Water quality indicators are therefore subject to **strong variability** (Fig. 4a-b, Fig 5 a-b), **masking anthropogenic effects**. From 1999-2008, the Washington State Department of Ecology collected and analyzed data on 16 water quality indicators at 21 core monitoring stations (Fig. 1) and determined a significant correlation of nitrate concentration and the oxygen saturation deficit between 0-50 m over time. Despite climatic fluctuations (Fig 3), a **significant increase in nitrate** concentration (Fig. 4a,b) developed **along the main urban corridor** spanning from Olympia to the Strait of Juan de Fuca and paralleled the increase in population between 1999-2008 (Fig. 2).

Nitrate is a significant contributor to marine eutrophication. The nitrate increase is significant enough to reflect the increase in the dissolved oxygen saturation deficit (Fig. 6). As both water entering Puget Sound from the Strait (Fig. 7) and rivers (Water Quality Monitoring Report, 2009) do not corroborate the increase in nitrate conclusively, more **attention** has to be dedicated **to the cause of Puget Sound's continued water quality degradation.**

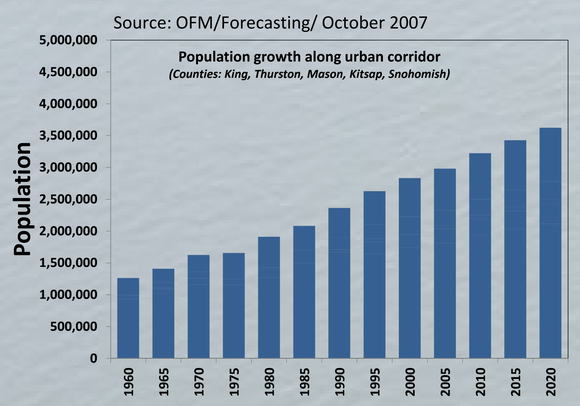

Fig. 2 Population growth is expected to increase and will continue to affect nitrogen discharge into Puget Sound

Ecosystem Variability

Ocean variability

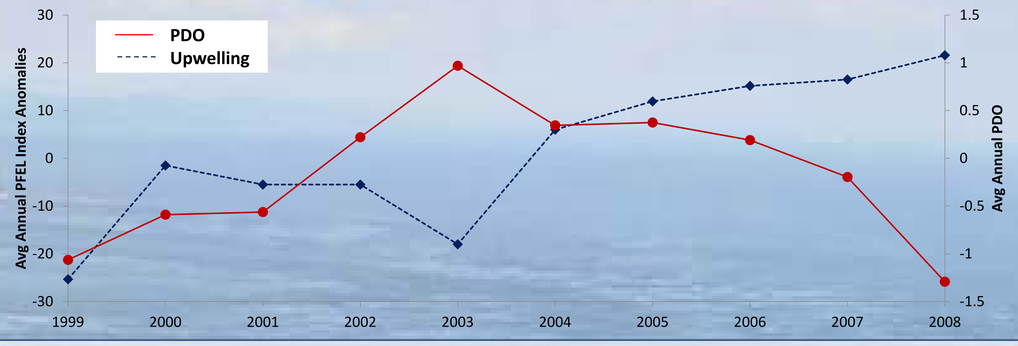

Fig. 3 **Ocean-climate variability indices relevant for Puget Sound; Pacific Decadal Oscillation and NOAA's index of upwelling (PFEL).** Indices show two different patterns: while ocean surface temperature (PDO index) showed a warm period in 2002-6, upwelling represented by the PFEL index anomalies for the Washington's coast (48°N 125°W) increased significantly over the last 10 years (Spearman Rank Correl. Coeff., $p<0.05$).

Puget Sound variability

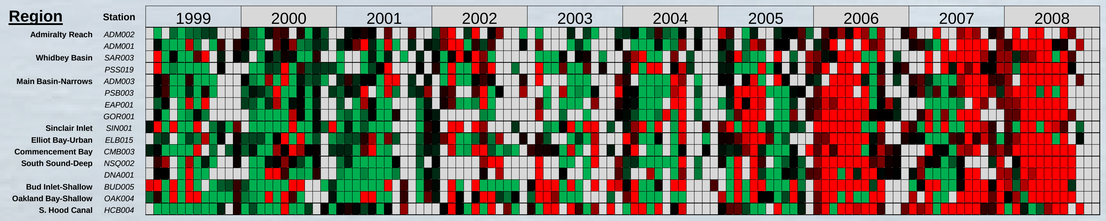

Fig. 4a **Monthly variability of nitrate concentrations from 16 stations in Puget Sound from 1999-2008.** Each pixel represents the median nitrate concentrations from 0, 10 and 30m depths for each sampling event. Color schemes represent the **25th percentile (green)**, the **50th percentile (black)** and the **75th percentiles (red)**. Grey represents where data are not available. Shifts from a prevalence of green to red indicate significant nitrate increases over the last 10 years.

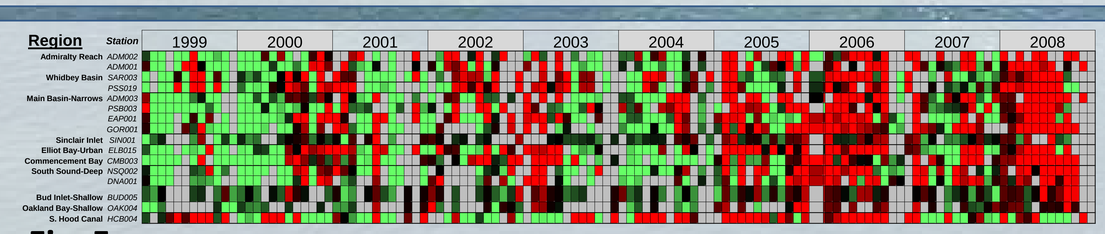

Fig. 5a **Monthly variability for the oxygen saturation deficit from 16 stations in Puget Sound from 1999-2008.** Each pixel represents the variability of depth integrated oxygen concentration minus the depth integrated theoretical saturated concentration for each sampling event. Color schemes represent the **25th percentile (green)**, the **50th percentile (black)** and the **75th percentiles (red)**. Grey represents where data are not available. Similar to nitrate the oxygen saturation deficit has increased over the last 10 years indicated by the green to red shift towards the right. Thus there is less oxygen available to support Puget Sound's ecosystem.

Conclusions

1. **Long-term trend of increasing nitrate and decreasing oxygen suggest a continued Puget Sound-wide intensification of eutrophication (Fig. 4a,b, Fig. 5a,b, Fig. 6).**
2. **Increased near-surface nitrate concentration in the Strait of Juan de Fuca (Fig. 7), indicative of increased nitrate export from inshore waters, is consistent with the nitrate increase within Puget Sound (Fig 4a).**
3. **Nitrate concentration and the dissolved oxygen saturation deficit strongly co-vary (Fig. 6), despite significant inter-annual variability. This supports the idea that inshore anthropogenic additions of nitrate are significant.**

Long-term trends

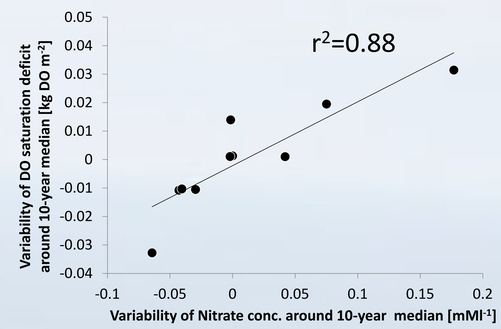

Fig. 6 **Correlation of yearly aggregated nitrate and dissolved oxygen (saturation deficit) for all 16 Puget Sound stations.** The graph represents a summary of 197,760 environmental data points.

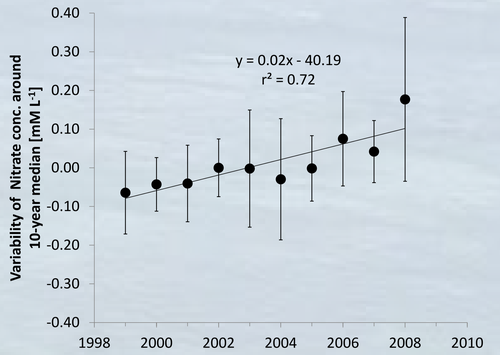

Fig. 4b **Increase in nitrate concentration in Puget Sound** (depth 0, 10, 30 m; dot = yearly median, bar = inter-quartile range). The graph summarizes 5,760 data points from 16 stations.

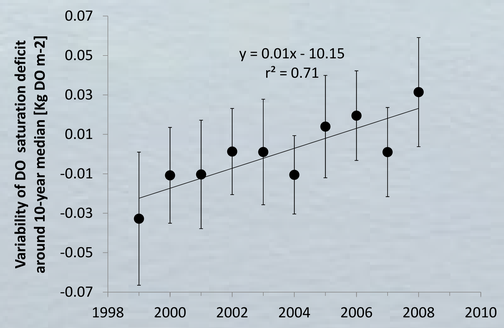

Fig. 5b **Increase in dissolved oxygen saturation deficit in P. Sound** (depth interval 0-50 m; dot = yearly median, bar = inter-quartile range). The graph summarizes 192,000 data points from 16 stations.

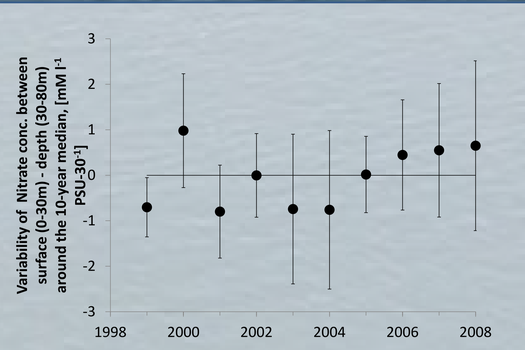

Fig. 7 **Increased nitrogen export** through the St. of Juan de Fuca for salinity normalized (30 PSU) nitrate data (dot = yearly median, bar = inter-quartile range).

References: Rivers and Streams, Water year 2008, (2009). Water Quality Monitoring Report , Publication No. 09-03-041

Poster prepared for the 2010 Ocean Sciences meeting in Portland, OR, USA