

Submarine Groundwater Discharge in the San Juan Archipelago and the Effects of
Nitrate Enrichment on *Zostera marina* L.

Christina Bonsell 1,2, Peter Swarzenski 3 and Sandy Wyllie-Echeverria 1

Blinks-NSF Research Fellowship 2011

1 Friday Harbor Laboratories, University of Washington, Friday Harbor, WA 98250

2 Department of Biology, University of California San Diego, La Jolla, CA 92093

3 U.S. Geological Survey, Center for Coastal & Watershed Studies, Santa Cruz, CA
95060

Contact Information:

Christina Bonsell

University of California San Diego

Department of Biology

9500 Gilman Dr. La Jolla, CA

cbonsell@ucsd.edu

Keywords: Submarine groundwater discharge, nitrate, eutrophication, *Zostera marina*

Abstract

Submarine groundwater discharge (SGD) can provide vital nutrients to coastal systems. Conversely, it can also lead to eutrophication of coastal waters, especially if the groundwater contains anthropogenic pollutants. This paper presents two studies encompassing this topic: a field study quantifying SGD at four sites in the San Juan Archipelago in the Northeast Pacific and a mesocosm experiment examining the effects of nitrate enrichment (30 μ M and 150 μ M added) on local *Zostera marina* L. SGD rates varied from essentially 0 to 16.7 \pm 22.4 cm/day. Results from the mesocosm experiment indicate that *Z. marina* under nitrate enrichment performs differently than those under control conditions. Under 30 μ M enrichment, photosynthetic capacity increased, while it decreased under 150 μ M.

Introduction

Submarine groundwater discharge (SGD) can contribute significantly to nutrient, carbon, and trace metal concentrations in coastal systems. This input of groundwater into nearshore waters has been shown to be comparable to riverine inputs in flux volume and usually exceeds river waters in terms of concentration of these materials (Moore 2010). These high nutrient concentrations in SGD can be a crucial nutrient source to N-limited coastal ecosystems (Giblin and Gaines 1990, Rutkowski et al. 1999). Although there has been little research on the ecological implications of SGD, the discharged nutrients are vital to certain coral reef and benthic macrophyte communities (Johannes 1980, Slomp and van Cappellen 2004). Conversely, the increased nutrients and the high iron concentration of SGD can also lead to conditions that promote algal blooms and

eutrophication, thus disturbing coastal ecosystems (Moore 2010). Although SGD is a known important nutrient source, it is a poorly quantified one, and its ecological effects remain opaque.

One of the major coastal ecosystems, seagrass beds provide food and shelter to marine life and waterfowl and have played an important cultural role for many coastal communities (eg. Kenworthy et al. 2006). Nutrient loading and eutrophication have been established as the cause of decline in many seagrass populations worldwide (Short and Wyllie-Echeverria 1996). Recently, in the San Juan Archipelago, in the Northeast Pacific, there has been a considerable decline in populations of eelgrass (*Zostera marina* L.), including a well documented disappearance in Westcott Bay, San Juan Island (Wyllie-Echeverria et al. 2003). Although the exact causes of declines in this area have yet to be determined, one hypothesis is a change in groundwater nutrient input due to increased human habitation – locals may be tapping into the groundwater, thus decreasing flux into the ocean, increasing groundwater nutrients via pollution, or a combination of the two.

In some areas of the Northeast Pacific, submarine groundwater discharge has been shown to contribute more inorganic nitrogen to coastal waters than surface runoff or atmospheric deposition (Swarzenski et al. 2007). The San Juan Archipelago consists of islands that, though often high relief, lack rivers. SGD, therefore, may be a major source of nitrogen into the local coastal area. Nitrate, unlike ammonia, the other major nitrogenous compound in SGD, is not readily fixed into the sediment. SGD-derived nitrate, therefore, has the potential to travel farther into a marine ecosystem. The growth of phytoplankton, epiphytes and macroalgae as a result of nutrient loading has been demonstrated many times to negatively impact seagrass by decreasing light availability

(eg Borum 1985, Short 1995, Burkholder et al. 2007). Other studies, however, have shown that that *Z. marina* in nitrate enriched mesocosms decreased in shoot density and exhibited structural degradation even when macroalgae and epiphytes were controlled for (Burkholder et al. 1992, Touchette et al. 2003).

To further understand the role of SGD nutrients in eelgrass health and distribution, we experimentally added nitrate to mesocosms containing local *Z. marina* to mimic a pulse groundwater pollution event to see how it would affect plant health and leaf growth. Using the radioactive tracer ^{222}Rn , which is highly concentrated in groundwater compared to seawater, we estimated rates of SGD at localized nearshore sites. With this information, we hope to begin to understand how SGD is affecting local *Z. marina* populations in the San Juan Archipelago, and how this may change with future human population increase and climate change.

Materials and Methods

SGD Time-Series

Submarine groundwater discharge monitoring equipment at each site was deployed for a five-day period, just below the low tide line. A Solinst CTD DIVER located at the sediment-water interface monitored salinity, temperature, and water level (via pressure). A submersible bilge pump, placed approximately a meter underwater, was plumbed to an air-water exchanger connected to a RAD7 ^{222}Rn detector. Time series data was recorded via the RAD7 every 30 minutes. Over a tidal cycle (12 hr) at the Jensen Bay site, just above the high tide line, a piezometer was placed about a meter into the

ground. Water was pumped from this using a peristaltic pump and was attached to an RAD7, as described above, to obtain a mean groundwater ^{222}Rn concentration.

Sites at four shallow embayments in the San Juan Archipelago were utilized. Three were located on San Juan Island (Garrison Bay, Jensen Bay, and Westcott Bay), one on Lopez Island (Fisherman Bay). All had recorded presence or past recorded presence of *Z. marina*. All sites were situated where the majority of the surrounding terrestrial land mass is glacial drift (Whiteman et al. 1983). Fisherman Bay has also been declining in recent years (S. Wyllie-Echeverria, *pers. comm.*).

Mesocosm experiment

Mesocosms consisted of three 540 liter tanks divided into three sections fed by seawater pumped from (location and depth). The plants used ($n=4/\text{section} = 12/\text{treatment}$) were taken from *Z. marina* harvested from Picnic Cove, Shaw Island, grown in an aquarium for two years. Each plant's rhizome was attached with plastic clips to a frame that was placed 1m below the water level. Plants were placed in stagnant ambient seawater in these tanks for five days, after which they were removed and scraped of epiphytes with a razor blade. Tanks then were drained, refilled with ambient seawater (ambient $\text{NO}_3^- < 10 \mu\text{M}$) and NaN_3 added to two of the tanks, increasing concentration by $30\mu\text{M}$ and $150\mu\text{M}$, respectively. As an unpolluted groundwater sample taken from a well near Garrison Bay only contained $1 \mu\text{M NO}_3^-$, these experimental conditions were meant to mimic polluted groundwater entering the system. The plants were added 20 hours later. Bubblers were fitted to each section to allow water flow. Each tank section was fitted with a HOBO temperature sensor. Odyssey PAR sensor were placed 30 cm

beneath the surface in the middle section of the control and high treatment tanks. Every other day, all plants were removed and half of the plants in each treatment were scraped of epiphytes.

Growth rate of each plant was measured using the hole punch method for the first (youngest) leaf: a pin was stuck through the shoot at a point about 1 cm below the meristem; at the end of the trial, the length from the meristem hole to the hole on the youngest leaf was recorded. Photosynthetic capacity (quantum yield) for the second youngest leaf of each plant was recorded using a pulse amplitude modulated (PAM) fluorometer 20 cm up the leaf from the meristem. The section of leaf used was dark-adapted by wrapping it with aluminum foil for at least 15 minutes before measurements were taken. This was done after the acclimation period and at the end of the experiment, seven days later. If the hole punch scars indicated that a new leaf had grown during the trial period, the third youngest leaf was used.

Results

SGD

The mean groundwater ^{222}Rn concentration at Jensen Bay was found to be 33460 disintegrations per minute/m³. At all study sites except Westcott Bay, a spike in ^{222}Rn concentration occurred at each lower low tide (Fig. 1). When this occurred, it corresponded with an influx of less saline groundwater (Fig. 1). Mean daily advection rates and SGD rates are displayed in Table 1.

Table 1. Mean rates of groundwater advection and discharge at each study site (cm/day).

Site	Mean Advection \pm SD (cm/day)	Mean SGD \pm SD (cm/day)
Fisherman Bay	5.4 \pm 8.4	16.7 \pm 22.4
Jensen Bay	4.7 \pm 7.4	9.2 \pm 14.8
Garrison Bay	4.8 \pm 7.3	9.3 \pm 14.6
Westcott Bay	0.9 \pm 3.1	N/A

Mesocosms

Tank temperatures

over the week-long trial varied

from 10.3 – 27.8 °C in the

control tank, 10.2 – 25.3 °C in

the low nitrate treatment tank,

10.0 – 25.0 °C in the high nitrate treatment

tank. Over the trial period, light levels in

the high treatment tank fell below those in

the control tank due to the presence of

phytoplankton (Fig. 2). A less severe

bloom was observed in the low treatment

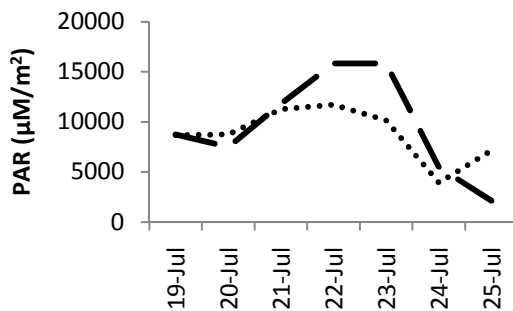


Figure 2. PAR ($\mu\text{M}/\text{m}^2$) over time for the control tank (dashed) and the high nitrate tank (dotted).

tank.

Two-way ANOVAs were used to detect differences in leaf growth and percent change in photosynthetic capacity (PC) with epiphyte presence and nitrate treatment as sources of variation. There were no significant interactions between effects of the presence of epiphytes and nitrate treatment ($p > 0.10$). Leaf growth, measured by elongation, did not significantly differ with nitrate treatment ($p > 0.10$) (Fig. 3). PC, however, did exhibit significant differences ($p = 0.048$). The presence of epiphytes did not have a significant impact on leaf elongation nor PC ($p > 0.10$). For this reason, as well as the fact the PC data was not normally distributed, a Kruskal-Wallis one-way ANOVA on ranks was performed. This identified an even greater difference among treatments

($p=0.024$). A Tukey pairwise multiple comparison detected no difference between control

and low treatments nor control and high treatments ($p>0.05$), but showed a difference between low and high treatments ($p<0.05$).

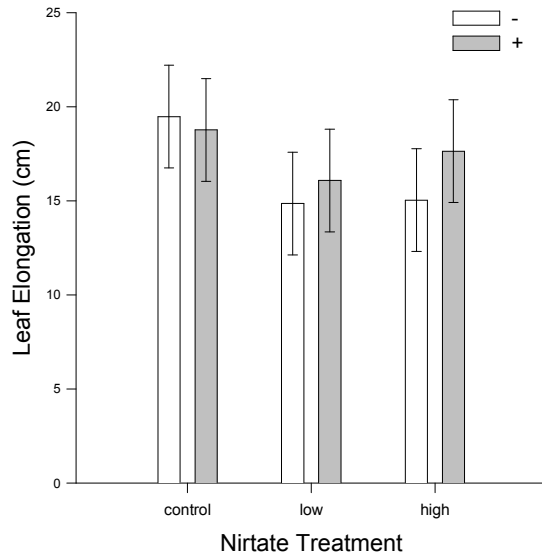


Figure 3. Leaf elongation over different nitrate treatments, showing with epiphytes (grey) and without (white). Results were not significantly different ($p>0.05$).

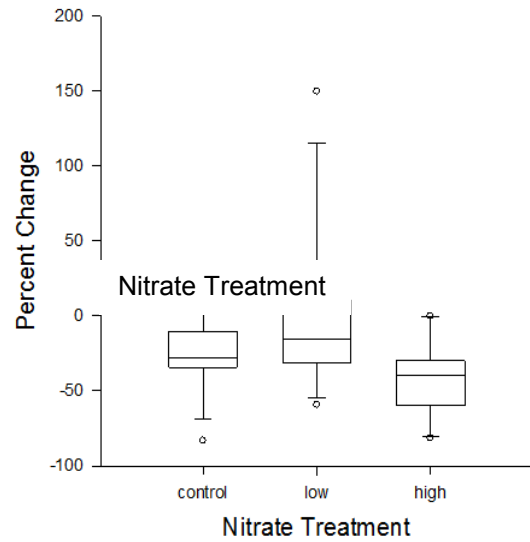


Figure 4. Percent change in photosynthetic capacity over different nitrate treatments. Results were not significantly different ($p>0.05$) between control and high nor control and low. Difference between low and high is significant ($p<0.05$).

Discussion

SGD

The amount of SGD entering the embayments we studied was fairly low, as is typical of temperate islands. The low readings observed at Westcott Bay may be a function of aquifer features, such as finer sediments, or simply a result of where samples were taken. Due to the significance of Westcott Bay when looking at *Z. marina* decline in the San Juan Archipelago, further investigation is warranted.

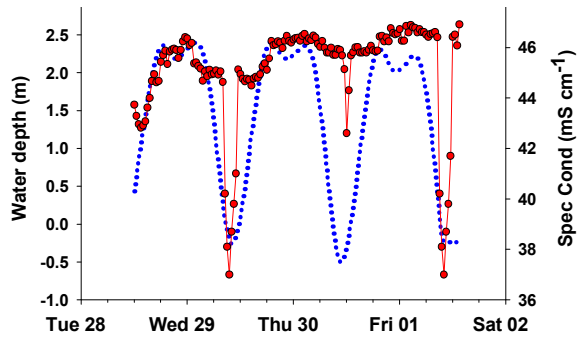
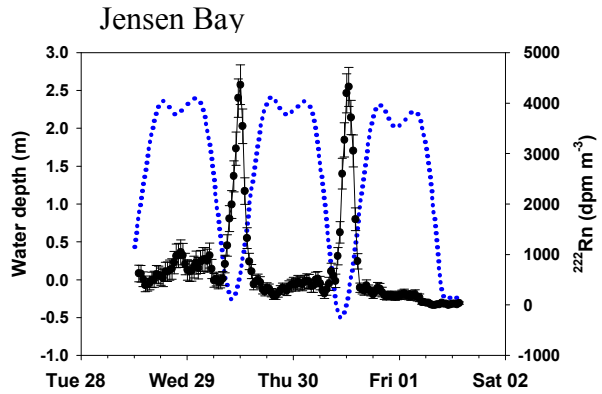
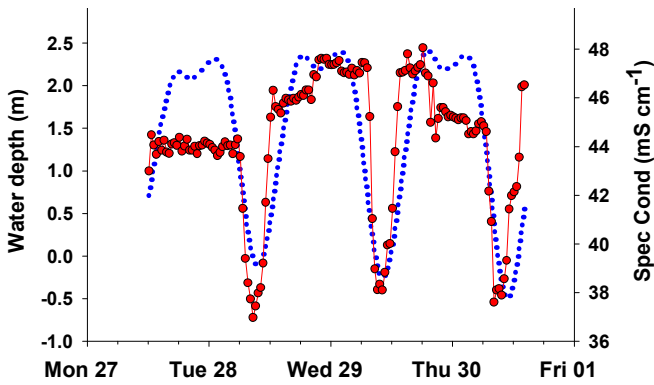
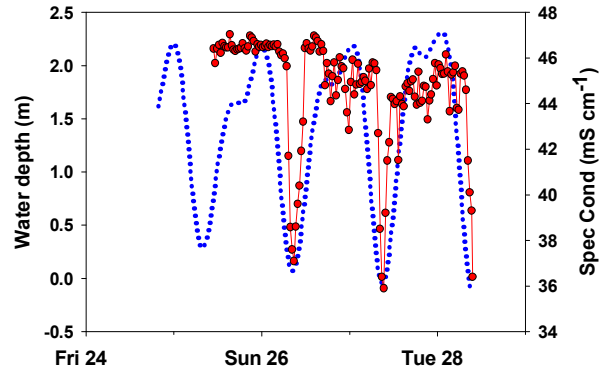
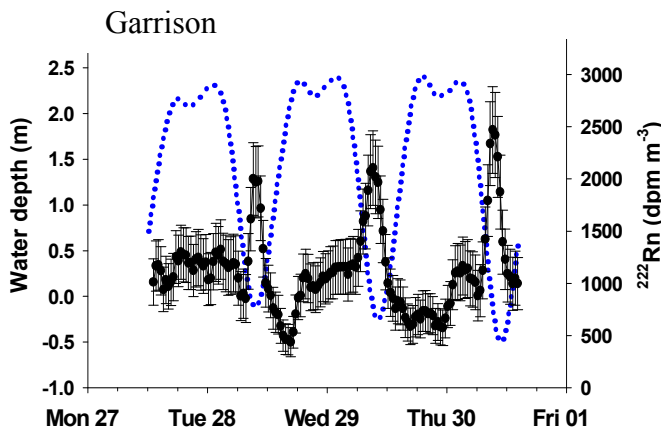
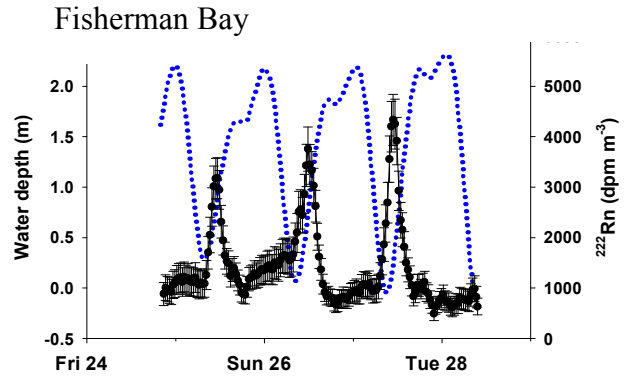
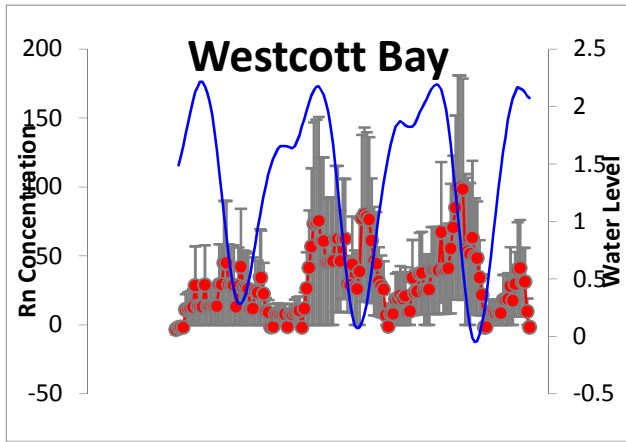


Figure 1. ^{222}Rn concentrations (dpm/m^3) and specific conductance (mS/cm), as well as sea water level (m), at each site.

Most houses in the San Juan Islands rely on septic systems. If poorly built or maintained, these can contribute significantly to the nutrients present in groundwater and therefore the nutrients transported to the nearshore system by SGD. This study did not examine the chemical constituents of the SGD at each site, and this should be included in future research.

Mesocosms

This experiment suggests that an acute pulse of nitrate into the water column affects the short term health *Z. marina*. Although there were no significant differences in leaf elongation, there was a trend of reduced growth in the enriched treatments compared to the control. Short et al. (1995) demonstrated that, under ammonium enrichment, this species will show decreased leaf growth over a period of months. Our experiment implies that nitrate enrichment can cause an analogous effect. The trend displayed by the percent change in photosynthetic capacity data showed a slight increase in PC under the 30 μM addition. This likely reflects the high energetic cost of active nitrate uptake which, in *Z. marina*, may lack feedback inhibition, and thus induce carbon limitation (Tourchette and Burkholder 2000). Studies using similar levels of nitrate enrichment have shown a comparable increase in *Z. marina* nitrate reductase activity under moderate enrichment, but not under high enrichment (Meier and Pregnall 1990). This suggests that *Z. marina*, when under comparatively lower levels of enrichment, is able to adaptively increase activities of certain biochemical pathways.

Though we tried to control the light reaching the plants by selectively removing epiphytes, the plankton bloom that occurred in the nitrate-enriched tanks may have

influenced the performance of affected plants. However, the higher PC exhibited by the low treatment plants indicates that this may not have been as an important factor as nutrient load. There are no known interactions between nutrient enrichment and light levels on *Z. marina* health and survival (Short et al. 1995).

Groundwater pollution due to increased coastal development has led to significant declines in *Z. marina* population area (Short et al 1996). This study hints that, while a single, pulse eutrophication event may not directly damage a healthy *Z. marina* population, an extended press disturbance or a repeated pulse disturbance may harm the population. In the San Juan Archipelago, there is high genetic diversity between geographically isolated populations of *Z. marina* (Wyllie-Echeverria et al. 2010). With this diversity comes different levels of biomass, shoot production and nutrient uptake rates (Hughes et al. 2009). As genetically distinct individuals are likely to respond differently to nutrient enrichment, populations of *Z. marina* may survive or perish under eutrophication depending on the site. Our results indicate that further research is needed to fully understand how coastal eutrophication caused by groundwater nutrients determines the presence and health of *Z. marina* populations in the San Juan Archipelago.

- Burkholder, J. M. et al. (1992) Water-Column Nitrate Enrichment Promotes Decline of Eelgrass *Zostera marina* - Evidence From Seasonal Mesocosm Experiments. *Marine Ecology-Progress Series* 81:163-178.
- Kenworthy, W. J. (2006). "Seagrass Conservation Biology: An Interdisciplinary Science for Protection of the Seagrass Biome" in: *Seagrasses: biology, ecology, and conservation* (p. 595). Dordrecht: Springer.
- Moore, W. S. (2010). The effect of submarine groundwater discharge on the ocean. *Annual Review of Marine Science*, 2(1), 59-88.
- Wyllie-Echeverria, S. et al. (2003). *Z. marina* declines in San Juan County, WA. Westcott Bay Taskforce Mini-Workshop 26, July 2003. 18. p.
- Short, F.T. et al. (1996). Long-term decline in eelgrass, *Zostera marina* L., linked to increased housing development. In: Kuo, J., R.C. Phillips, D.I. Walker and H. Kirkman (eds.). *Seagrass Biology: Proceedings of an International Workshop, Rottneest Island, Western Australia, 25-29 January 1996*. Nedlands, Western Australia: Sciences UWA. pp. 291-298.
- Short, F.T. and S. Wyllie-Echeverria. (1996). Natural and human-induced disturbance of seagrasses. *Environmental Conservation* 23:17-27.
- Short, F.T. et al. (1995). Mesocosm experiments quantify the effects of eutrophication on eelgrass, *Zostera marina*. *Limnol. Oceanogr.* 40:740-749.
- Slomp, C., and VanCappellen, P. (2004). Nutrient inputs to the coastal ocean through submarine groundwater discharge: Controls and potential impact. *Journal of Hydrology*, 295(1-4), 64-86.
- Johannes R. E. (1980). The ecological significance of the submarine discharge of ground water. *Mar. Ecol. Prog. Ser.* 3:365-73.
- Touchette, B. W. et al. (2003). Variations in eelgrass (*Zostera marina* L.) morphology and internal nutrient composition as influenced by increased temperature and water column nitrate. *Estuaries*, 26(1), 142-155.
- Touchette B. W. and M. Burkholder (2000). Review of nitrogen and phosphorus metabolism in seagrasses. *Journal of Experimental Marine Biology and Ecology* 250:133-167.
- Burkholder, J. M. et al. (2007). Seagrasses and eutrophication. *Journal of Experimental Marine Biology and Ecology*, 350(1-2), 46-72.
- Giblin, A. and A. Gaines (1990) Nitrogen inputs to a marine embayment: The importance of groundwater. *Biogeochemistry* 10, 309-328.

Whiteman, L. A. et al. (1983) Estimates of ground-water recharge from precipitation to glacial-deposit and bedrock aquifers on Lopez, San Juan, Orcas, and Shaw islands, San Juan County, Washington; WRI.

Swarzenski, Peter W. et al. (2007). Geochemical and Geophysical Examination of Submarine Groundwater Discharge and Associated Nutrient Loading Estimates into Lynch Cove, Hood Canal, WA. *Environmental science & technology* 41.20: 7022-9.

