

## Sockeye Restoration - Lake Fertilization:

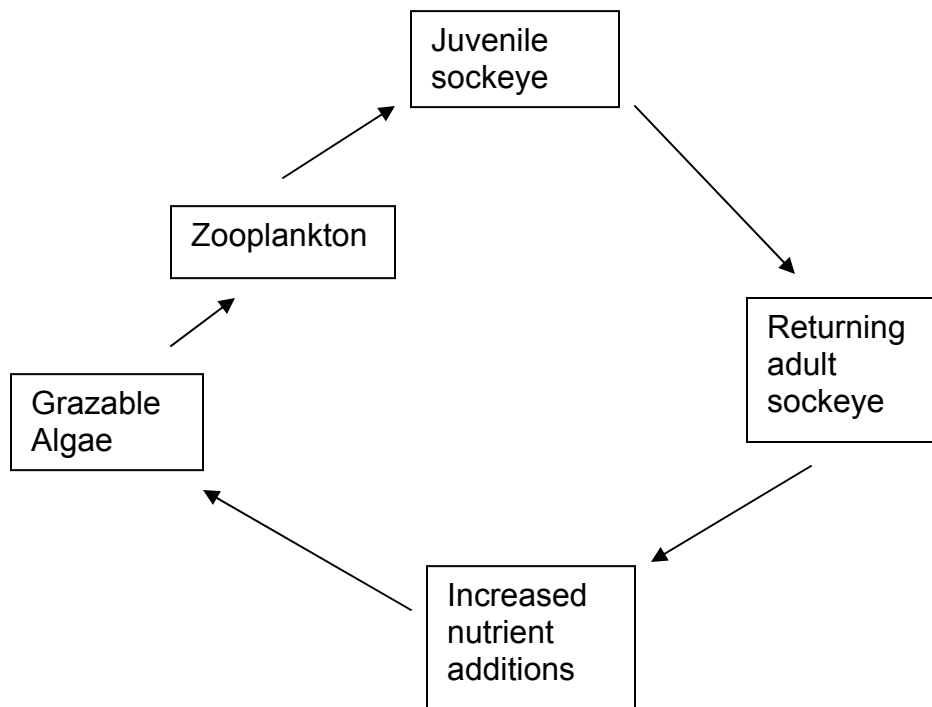
D.J. McQueen (don\_mcqueen@telus.net)

Bert Svanvik (Berts@namgis.bc.ca)

### Lake Fertilization Theory:

Ricker (1962) showed that over a very broad geographical range extending from Oregon to Alaska, there is a positive relationship between smolt size and marine survival. More recently, this positive relationship has been verified for Long Lake (Hyatt et al. 2000) and Chilko Lake (Bradford et al. 2000), and is also in evidence for the Nimpkish Watershed (see Chapter 4 in the Nimpkish Watershed Recovery Plan). Together these results suggest that if a way could be found to artificially increase smolt size, marine survival might be substantially enhanced. This is the goal of lake fertilization (Wilson & Halupka 1995, Stockner & MacIsaac 1996, Bilby et al. 1996, Larkin & Slaney 1997, Ashley & Slaney 1997, Cederholm et al. 1989, 1999, 2000, Stockner et al. 2000).

Lake fertilization theory is based on the observation that decomposing bodies of sockeye salmon (*Oncorhynchus nerka*) spawners, can contribute a substantial fraction (15-25%) of the nutrient load that has historically fertilized sockeye nursery lakes (see figure below). This natural "fertilization" contributes nutrients (phosphorus, nitrogen, carbon) that stimulate the growth of algae. The algae provide a food source for zooplankton, and zooplankton contribute



to the diets of juvenile sockeye salmon. In recent years; over fishing, habitat destruction, and climate-induced marine mortality has tended to break the cycle

by depressing the numbers of adults that return to the nursery lakes. This has reduced the magnitude of both egg deposition and nutrient additions that influence subsequent generations of young. The objective of lake fertilization is to replace some of the limiting nutrients (phosphorus and nitrogen) that are no longer provided by returning salmon and thereby rebuild the stock through increased juvenile growth and survival.

On the west coast of Canada, large-scale lake fertilization began with an eight year (1969-76) "pilot experiment" on Great Central Lake, Vancouver Island. The results of this careful piece of early work are complex but, in a nutshell, the experiment worked well and led to the subsequent fertilization of an additional 20 lakes (1979-present). These lakes were generally large (>500 ha), often remote and, in the early years, were fertilized using aircraft. The resulting scientific analyses showed that in some lakes, juvenile sockeye growth-rates were increased, while in others, the results were much less certain. There are three basic problems. (1) Juvenile sockeye productivity is almost always associated with enhanced growth and production of zooplankton; which provide food for juvenile sockeye. However, these newly produced zooplankton also provide food for other fish; most notably the threespine stickleback (*Gasterosteus aculeatus*), and also for large invertebrate predators. All of these plankton-eating species (sockeye, other fish, carnivorous zooplankton) compete for the fertilizer-induced herbivorous zooplankton; and it seems that in some cases juvenile sockeye lose the resulting competition. (2) When fertilizers are added to a lake, it is often difficult to predict which zooplankton species will be stimulated. All herbivorous zooplankton compete for increased algal biomasses, and in theory (Brooks & Dodson 1965), the largest species should dominate. Because juvenile sockeye have a strong preference for large-bodied zooplankton such as *Daphnia* (Eggers et al. 1978) fertilization-induced increases in productivity can have significant effects on sockeye growth rates. However, this can only happen when large-bodied zooplankton species are present in sufficient numbers at the onset of the fertilization period. When large-bodied (> 0.4 mm length) zooplankton species are rare or absent, fertilization serves only to stimulate small-bodied (< 0.4 mm length) zooplankton which are poor food sources for sockeye and which are very vulnerable to the suite of competing invertebrate carnivores noted above. (3) When fertilizers are added to lakes, classic limnological theory states that small-bodied algae should be the first to benefit because they have large surface to volume ratios which facilitates rapid nutrient uptake. When this occurs juvenile sockeye can benefit because small algae are generally very grazable by zooplankton which increase rates of productivity thus providing more food for sockeye. However, there have been many cases where "classical limnological theory" has broken down and increased rates of nutrient additions have only served to stimulate the growth of large or ungrazable algae. When that occurs, zooplankton do not benefit and sockeye food supply is not increased

In summary, there are three issues that directly relate juvenile sockeye production to the types of fish, zooplankton and algae that are available in

specific sockeye nursery lakes. When large bodied herbivores are abundant, we might predict that sockeye growth and production will increase. Conversely, when large invertebrates or competing fish species (such as stickleback) are abundant, we might predict that sockeye production will be lower. When these two factors are combined, we might predict that fertilizer induced stimulation of algae will cascade up to the invertebrate predator rather than sockeye. On the other hand, when invertebrate carnivores are rare, and large herbivores are abundant, fertilization is likely to cascade up to the sockeye, resulting in increased rates of growth and production. Finally, all of this is predicated on the assumption that fertilizer additions will stimulate algae that can be grazed by zooplankton.

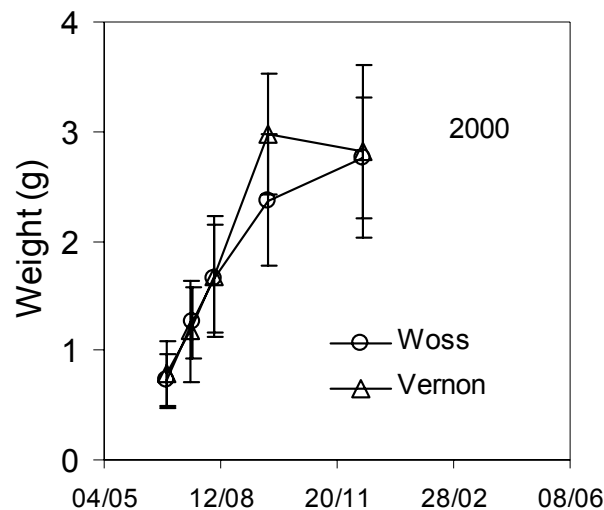
### **The Woss Lake and Vernon Lake Study**

To determine which of this series of pelagic food web pathways were most important in Woss Lake, we undertook an analysis of food web structure in both Woss (fertilized) and Vernon (control) Lakes. Since its inception this has been a collaborative program. During the first three years (2000-02) the program was run by the Gwa'ni Hatchery, Nimpkish Resource Management Board, Fisheries and Oceans Canada and York University. More recently (2003-08) the work has been funded by the Pacific Salmon Endowment fund and run by Gwa'ni Hatchery, Nimpkish Resource Management Board, and Fisheries and Oceans Canada. The program has been structured to deliver the following analyses: (1) Beginning at the top of the food web, we measure sockeye growth rates, diets, diel migration patterns and water temperatures. These data are then used in a bioenergetic analysis to estimate food consumption by juvenile sockeye. (2) We then assess zooplankton population abundances, biomasses, length-weights, egg numbers. We know that all zooplankton were not going to be equally good food sources for juvenile sockeye, so it is not enough to calculate overall zooplankton density and production rates. What we need to calculate is species-specific rates of production by zooplankton and consumption by sockeye. This analysis is intended to allow us to determine whether or not the sockeye can graze down all the "good food species", leaving other species that are much less suitable as food sources. (3) We then calculate the percentage of species-specific zooplankton production that is consumed by sockeye. When consumption approaches or exceeds production, we know that food limitation is a problem and in the long term we can react to this problem by adding more or less fertilizer or by increasing or decreasing rates of sockeye fry recruitment (by increasing spawner abundance or through fry outplanting). (4) Finally, because "bottom-up" sockeye enhancement theory is based on the assumption that fertilizer additions will stimulate algae that can be grazed by zooplankton, we monitor rates of nutrient addition and we complete species-specific assessments of algal species composition. Our objective is to determine whether the algal genera that were stimulated by the fertilizer additions were also grazable by zooplankton.

## Woss and Vernon Lake Results

**Results Year 2000:** During the first year of fertilization (year 2000), the fertilizer was added during July and August. The water chemistry data showed that the methods used to distribute fertilizer (from a boat) were successful and that post-addition phosphorus concentrations were relatively even across the lake. In addition, there was no indication that fertilizer was lost into the hypolimnion. The zooplankton data showed that both lakes contained abundant populations of zooplankton species that have been shown to be acceptable food sources for juvenile sockeye. The fish data clearly showed that the juvenile sockeye in both lakes grew much more quickly than in previous years. However, comparisons of growth rates between the fertilized lake (Woss Lake) and control (Vernon Lake) revealed no differences in growth rates (figure 2). This result was a surprise because up to this point in the analysis we had seen that, (1) suitable zooplankton were abundant on both lakes, and (2) fertilizer additions into Woss Lake during July and August 2000 had a substantial effect on phytoplankton biomass which increased approximately 10 times (figure 3). The question was, why didn't the zooplankton in Woss lake consume all of this extra phytoplankton and show greatly increased production rates and biomasses? Certainly the sockeye could not have prevented them from doing so.

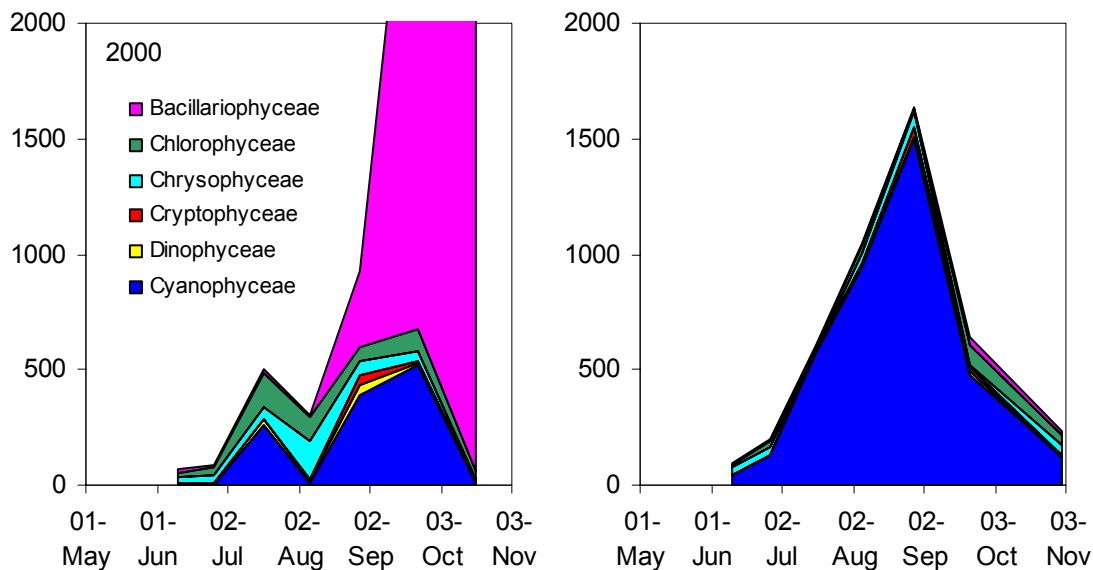
**Figure 2:** Weights of juvenile sockeye in Woss and Vernon Lakes during year 2000.



The answer to this question turned out to be that the addition of fertilizers to Woss Lake resulted in the development of a substantial bloom of *Rhizosolenia eriensis*. This large diatom is very special because its shape creates a large surface-to-volume ratio which allows it to out-compete other algal species for nutrients, but at the same time it is so large that it can't be eaten by zooplankton.

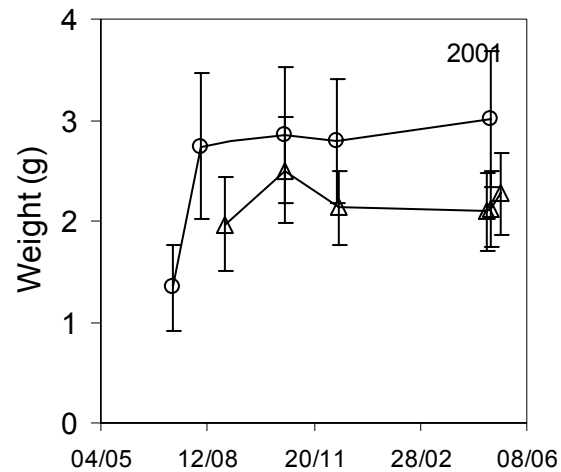
This bloom of *Rhizosolenia eriensis*, meant that the zooplankton were unable to take advantage of the nutrients that were added, therefore zooplankton production did not increase and juvenile sockeye failed to show increased growth rates. In a nutshell, the year 2000 fertilization of Woss lake was a failure because the wrong species of algae was stimulated by the fertilizer addition and the nutrients added through fertilization, were unable to stimulate increased zooplankton production (figure 4).

**Figure 3:** Woss right & Vernon left. Year 2000 phytoplankton biomass (Y axis as  $\text{mm}^3$  per  $\text{m}^3$ ). Phytoplankton classes are colour coded. Almost all of the bacillariophyte (diatom) increase in Woss lake was due to a bloom of *Rhizosolenia eriensis*.

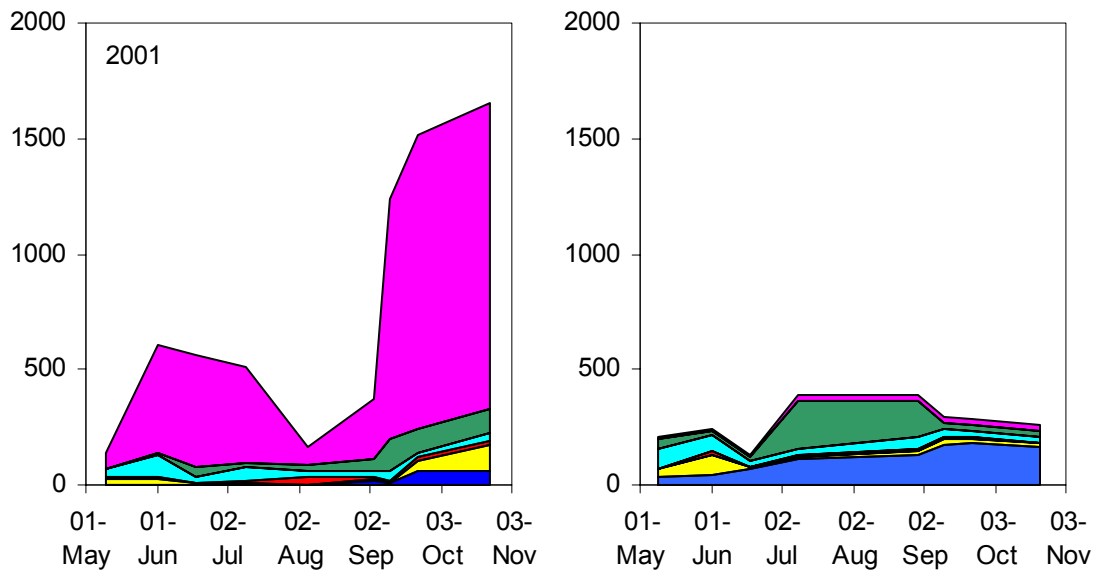


**Results Year 2001:** During the second year of the experiment (year 2001) the rate and timing of fertilizer addition was modified in order to reduce the likelihood of promoting the growth of ungrazable algae such as *Rhizosolenia eriensis*. Fertilizer applications were begun on May 07, 2001 and continued through to the end of August. The loading rates increased through May leveled off at a maximal rate during June and then tailed off during July and August. Based on available data it seems that the year 2001 fertilization was quite successful. Early addition of nutrients almost totally eliminated *Rhizosolenia eriensis*. (figure 5, 6). Diatoms did grow, but the biomasses tended to be smaller and the species composition tended to favor *Asterionella* (another diatom, but one that is more zooplankton-friendly). In addition, the Woss Lake fish grew very quickly (figure 4) during the summer, achieving sizes that were significantly greater than in the unfertilized control lake (Vernon) and this difference persisted through to March 2002 when juveniles from both lakes left as smolts.

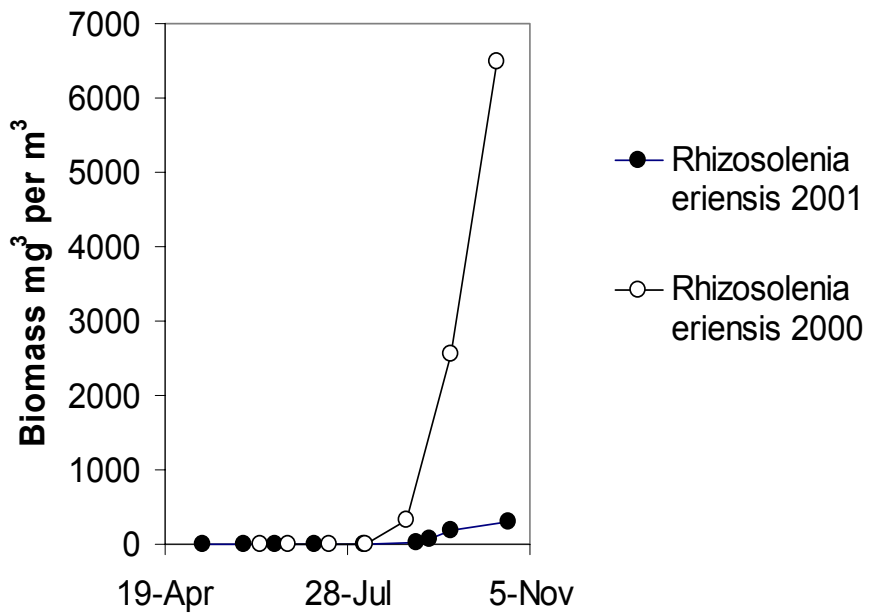
**Figure 4:** Weights of juvenile sockeye in Woss and Vernon Lakes during year 2001. Woss Lake fish are denoted by circles, Vernon by triangles.



**Figure 5:** Woss right & Vernon left. Year 2001 phytoplankton biomass as  $\text{mm}^3$  per  $\text{m}^3$ . Phytoplankton classes are colour coded as above. Almost none of the bacillariophyte (diatom) increase in Woss lake was due to a bloom of *Rhizosolenia eriensis*.

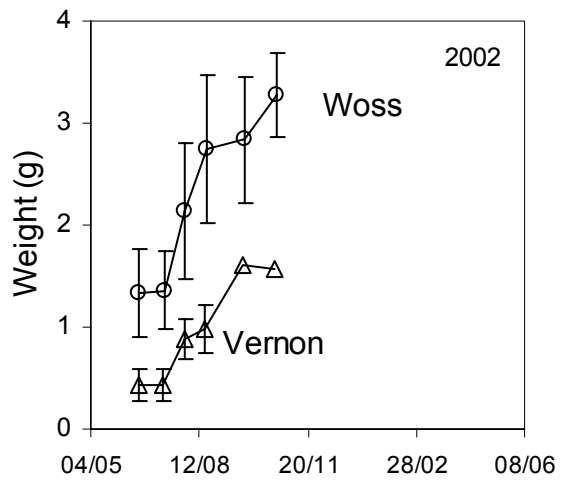


**Figure 6:** Relative concentration of *Rhizosolenia eriensis* during year 2000 and 2001 at Woss Lake.

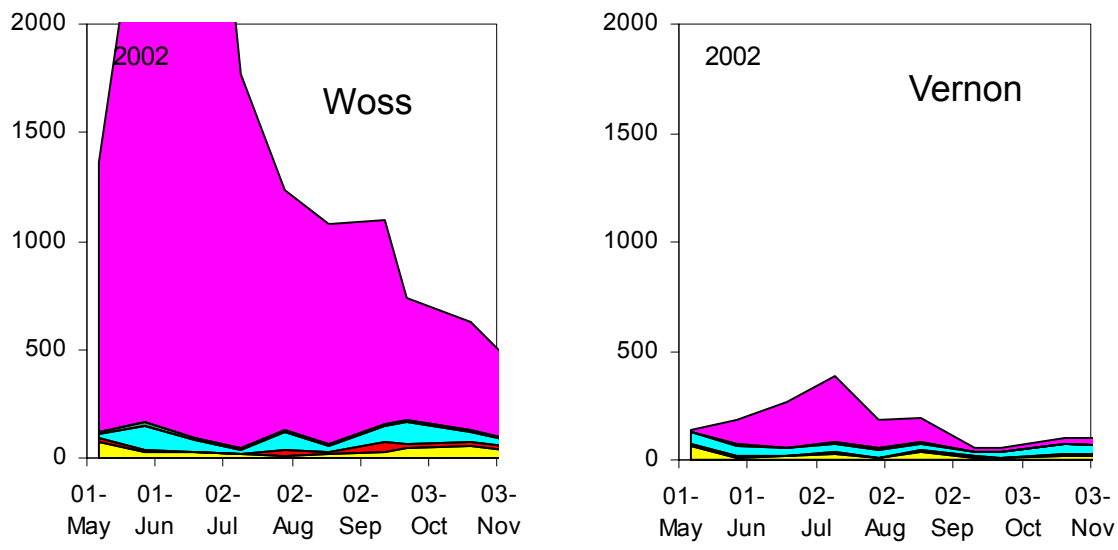


**Results Year 2002:** Year 2002 was the third “experimental year”. This was the most successful year to date. In Woss lake, sockeye growth was rapid and at the end of the summer Woss lake fish were almost twice as large as they were in the unfertilized control Lake (Vernon - figure 7).

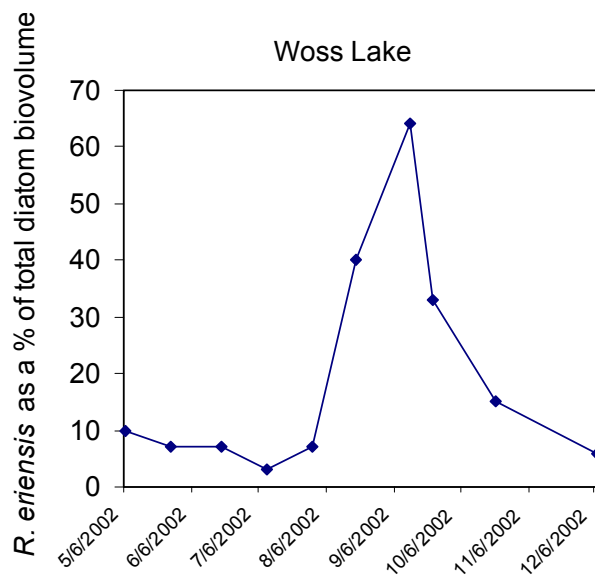
**Figure 7:** Weights of juvenile sockeye in Woss and Vernon Lakes during year 2001.



**Figure 8:** Woss right & Vernon left. Year 2002 phytoplankton biomass as mm<sup>3</sup> per m<sup>3</sup>. Phytoplankton classes are colour coded as above.



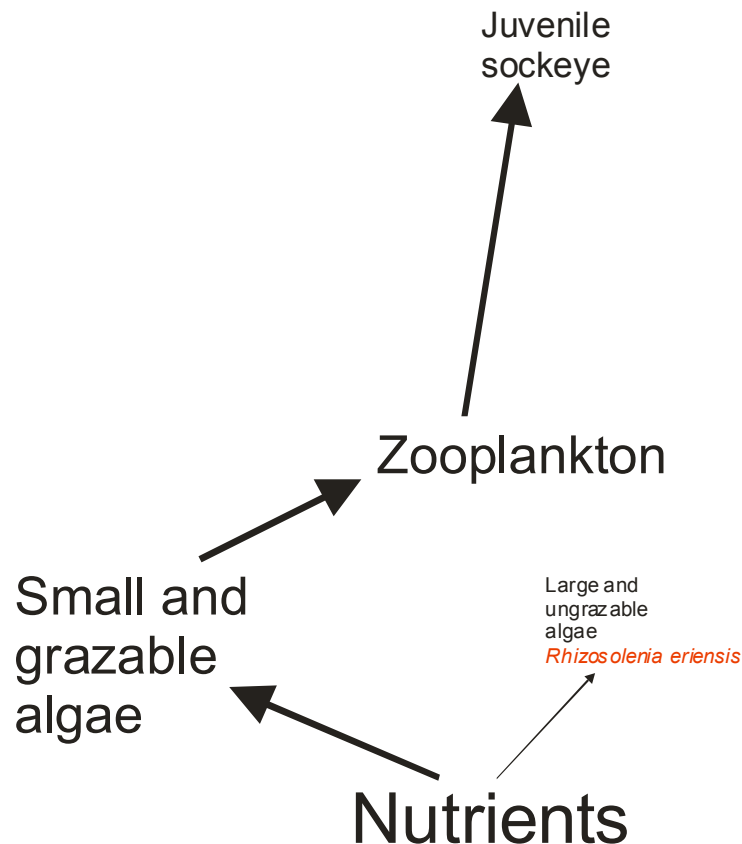
**Figure 9:** *Rhizosolenia eriensis* as a percentage of total diatom biovolume.



During 2002, in Woss Lake, a substantial bloom of diatoms developed during the spring (pink in figure 8). However, in contrast to the year 2000, the inedible diatom *Rhizosolenia eriensis* accounted for a relatively small portion of the total diatom biomass (figure 9). This was especially true in the spring, when diatom biomass was dominated by *Tabellaria*, a grazable genus. The result was that during the spring of 2002, zooplankton production rates were very high (data will be provided in a subsequent update of this web site) and juvenile sockeye growth rates were also high (figure 7).

Overall, during the spring of 2002, lake fertilization at Woss Lake was associated with substantial abundances of grazable algae, which stimulated good zooplankton growth and therefore, good growth rates for juvenile sockeye (figure 10). At the end of 2002, the general consensus among NRMB members was that we had learned to successfully fertilize Woss Lake and the future seemed assured.

**Figure 10:** Year 2002 food web structure in Woss lake.



**Results Year 2003:** This is the fourth year for the fertilization program in Woss Lake. Fertilization began on April 3<sup>rd</sup>, a couple of weeks earlier than last year. The Gwa'ni Hatchery crew applied 729 liters of fertilizer to the lake the first day and the subsequent applications were increased to 1,426 liters/two times/week until June 10<sup>th</sup> and then the amount was reduced to 698 liters/two times / week (see schedule). In mid May the fertilization crew started to take the water samples once a week from the Woss lake outlet, storing the samples at the hatchery. Barry Hanslit from the Pacific Biological Station would pick-up the samples and take them to the Pacific Biological Station in Nanaimo and from there they would be sent to the Water chemistry lab. The Gwa'ni Hatchery has applied the fertilizer in all four years using the hatchery's modified aluminum herring punt with a 750 liter holding tank to apply the fertilizer (see picture).

There were 3 different loads of fertilizer delivered to the Woss lake compound this year; the first load was delivered on March 26<sup>th</sup>, the second load delivered May 30<sup>th</sup>, and the third load delivered on July 18<sup>th</sup>. The fertilizer was delivered in different mixture ratios of Nitrogen:Phosphorus starting at 30:1 in April and May, increased to 37:1 in June and early July and then increased again to 45:1 in late July and August to adjust for the reduction in nitrogen levels in the lake. The last load of fertilizer was applied on August 22, 2003.



## Woss Lake Fertilization 2003 Schedule (Actual)

<b>Week</b>	<b>Date 2003</b>	<b>Liters fertilizer added each day</b>	<b>Crew from Gwa'ni Hatchery</b>
1	3-Apr	729	Ben / Ken
2	7-Apr	1426	Ben / Lawrence
	10-Apr	1426	Ben / Lawrence
3	15-Apr	1426	Lawrence / Ken
	22-Apr	1426	Lawrence / Ken
4	25-Apr	1426	Lawrence / Ken
	29-Apr	1426	Lawrence / Ken
5	2-May	1426	Lawrence / Ken
	6-May	1426	Len / Peter
6	9-May	713	Len / Peter
	12-May	713	Len / Ken
	13-May	1426	Len / Ken
7	16-May	1426	Phil / Ken
	20-May	1426	Ben / Len
8	23-May	1426	Ben / Len
	27-May	1426	Ben / Len
9	30-May	1426	Ben / Len
	3-Jun	1426	Phil / Len
10	6-Jun	1426	Lawrence / Ken
	10-Jun	698	Ben / Ken
11	12-Jun	698	Phil / Ken
	17-Jun	698	Phil / Len
12	20-Jun	698	Phil / Ken
	24-Jun	698	Phil / Ken
13	27-Jun	698	Phil / Ken
	1-Jul	698	Phil / Ken
14	4-Jul	698	Phil / Aaron / Donald
	8-Jul	698	Len / Jeremy
15	11-Jul	698	Hank
	15-Jul	698	Len / Ken
16	22-Jul	698	Hank
	25-Jul	698	Ben / Lawrence
17	29-Jul	698	Ben / Lawrence
	1-Aug	698	Ben / Lawrence
18	4-Aug	698	Ben / Lawrence
	8-Aug	698	Ben / Lawrence
19	12-Aug	698	Ben / Lawrence
20	15-Aug	698	Ben / Lawrence
21	20-Aug	698	Ben / Lawrence
22	22-Aug	698	Ben / Lawrence
	<b>TOTAL Liters</b>	<b>39628</b>	

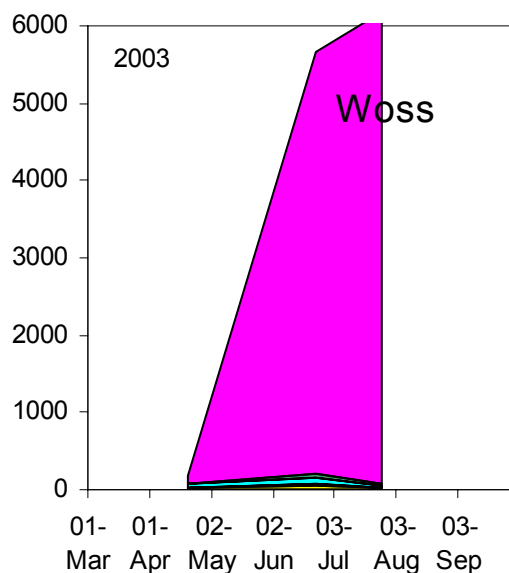
At this time (September 2003) the 2003 monitoring program is only partially complete (see table below). Water chemistry, algae and zooplankton have been collected for several dates and as of mid-September, fish collections have been completed for two dates. These collections will continue through the fall.

**Table:** Sampling schedule and data collected in Woss Lake and in a control lake (Vernon Lake) during year 2003.

Date 2003	Oxygen and temp.	Water chem	Zoop sampled	Transect echo-grams	Fish lengths and weights	Fish densities
April 23	y	y	y			
May 22	y	y	y			
June 27	y	y	y	y	y	y
July 17	y	y	y			
Aug 21	y	y	y			
Sept 17	y	y	y	y	y	y
October	y	y	y	y	y	y
Nov 08	y	y	y	y	y	y
Dec.	y	y	y	y	y	y

Because the data are only partially complete it is impossible to draw any firm conclusions about the results of the 2003 fertilization. However, the small amount of data that is available suggests that during the spring, *Rhizosolenia eriensis* again dominated the plankton (figure 11). The blooms developed

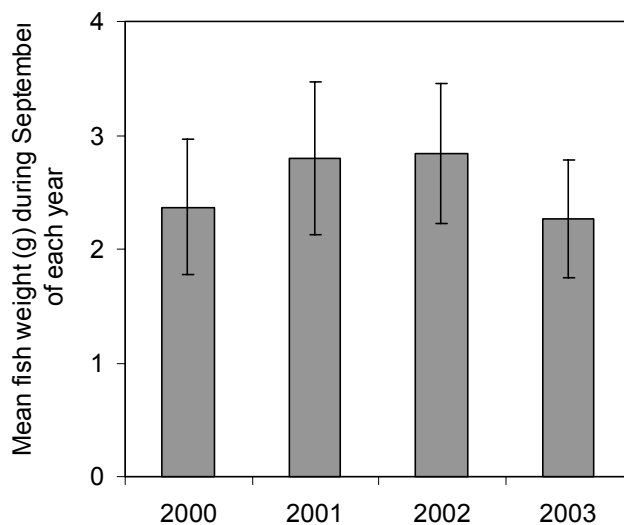
**Figure 11:** Woss Lake, year 2003 phytoplankton biomass as  $\text{mm}^3$  per  $\text{m}^3$ . Phytoplankton classes are colour coded as above.



earlier than ever before and by July 27 (the last sample counted) had reached biomasses that were greater than ever before. Virtually 100% of the bloom comprised *Rhizosolenia eriensis* (the clear glass-like algae in middle-left in the enclosed picture). As noted earlier, this species is large and spiked, and cannot be eaten by zooplankton.

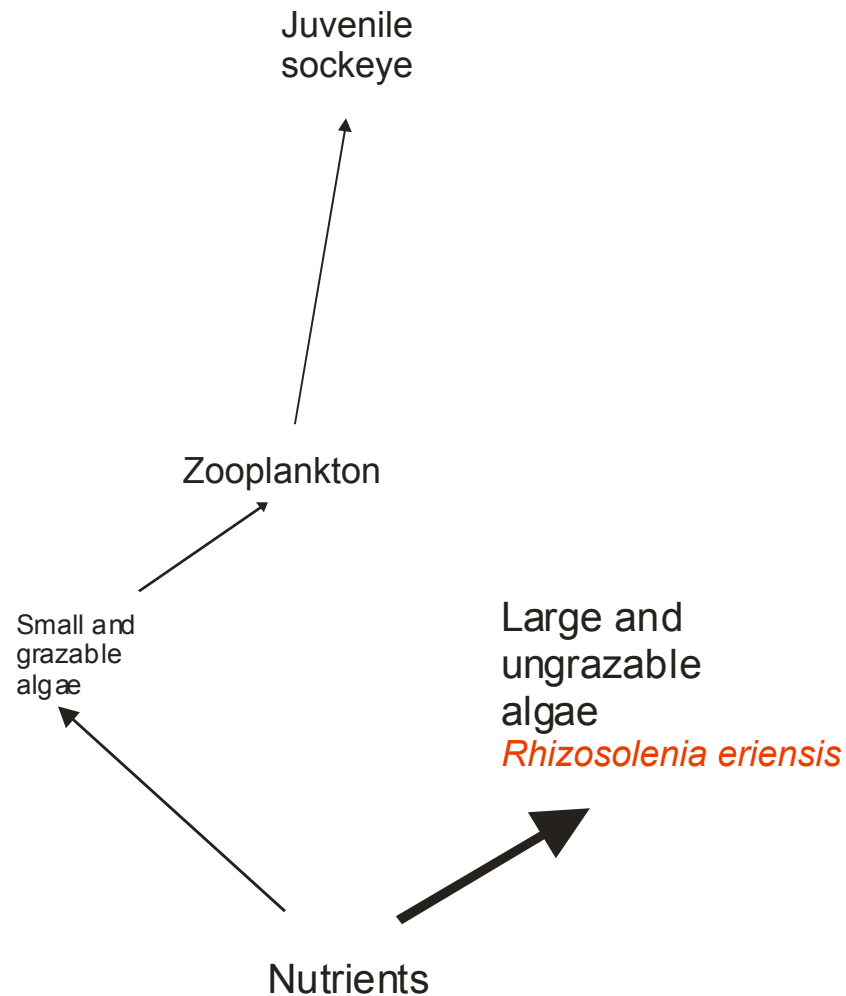


**Figure 12:** Woss Lake mean ( $\pm 1$  sdev) sockeye weights recorded in September.



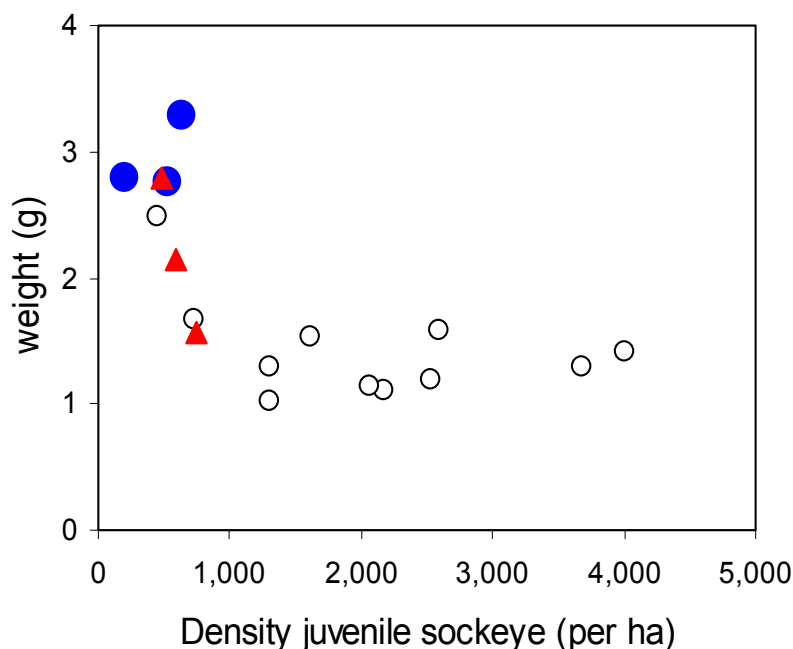
At the moment, sockeye growth (figure 12) data for 2003 are very preliminary and incomplete, however a good sample (n=250) was collected on September 17, 2003 and, when this is compared with September sockeye weight samples collected in other years (figure 12), we see that the 2003 weights are about equivalent to those observed in 2000. In a nutshell it seems that the Woss Lake food web has again been disrupted (figure 13), so that most of the energy added through fertilization is consumed by *Rhizosolenia eriensis* and thus never becomes available to zooplankton or fish (figure 13). It is certainly possible that during the fall, conditions will change and sockeye growth rates will increase, but at the moment the spring-summer sockeye growth rates do appear to be lower than expected.

**Figure 13:** 2003 Woss Lake spring-summer food web.



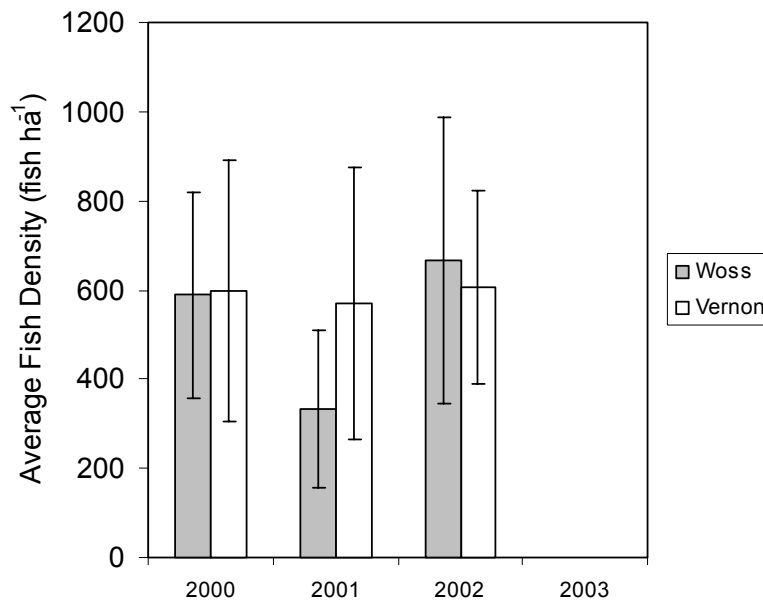
It is well known that in BC coastal lakes, sockeye growth rates are negatively influenced by fish density. Historically this has certainly been true in Woss lake (figure 14). It might therefore be argued that during 2003, population densities may have been exceptionally high, thus accounting for the observed September weights.

**Figure 14:** Mean annual fall sockeye juvenile weight with respect sockeye population density in Woss Lake. The open circles are from collections made during the 1980s and 1990s. The blue dots are from Woss lake collections made during 2000-2002. The red triangles are from Vernon lake during 2000-2002.



During 2000-2002, Woss Lake densities averaged about 500 sockeye per ha (figure 15), which translates into approximately 650,000 sockeye in the entire lake. Given that during the spring of 2003, staff at the Gwa'ni Hatchery augmented the natural population by stocking approximately 1,000,000 hatchery and cassette-reared juveniles into Woss Lake, there is some possibility that the 2003 densities may have been higher than the levels recorded during 2000-2002. At the moment the density data are too sparse to make any realistic assessment. Throughout the fall at least three additional acoustic surveys will be conducted, and when those data are available it will be possible to assess the density hypothesis.

**Figure 15:** Mean sockeye densities ( $\pm 1$  sdev) observed in Woss and Vernon lakes during 200-2002.



**The future:** During the next 4 years, with continued support from DFO and new support from the Pacific Salmon Endowment Fund, and Canfor; it seems likely that the NRMB will continue the fertilization of Woss Lake. The major question to be addressed are (1) will it be possible to discourage the growth of *Rhizosolenia eriensis*, and (2) will it be possible to assess the relative in-lake survivals of stocked and wild-type sockeye in Woss Lake. During the next year, the NRMB may also consider the possibility of fertilizing Vernon Lake. In many ways the Vernon experiment will be even more interesting than the Woss. Our zooplankton data show that Vernon has higher densities of total zooplankton, more *Daphnia*, more *Bosmina* and also has *Hesperdaptomus kenai* a large species that is known to be an excellent food source for juvenile sockeye. In addition it had no *Epischura nevadensis* a potential food competitor. Also, *Rhizosolenia eriensis* was observed only during the very late fall and only in very low concentrations. Together these characteristics suggest that on a aerial basis, Vernon may prove to be a better sockeye producer than Woss.

**Acknowledgement:**

This four year program is both “experimental” and “collaborative”. Over the years, direct funding has come from the Nimpkish resource Management Board, an NSERC grant to D.J. McQueen and from the Pacific Salmon Endowment Fund. Logistical and direct support has been provided by DFO Salmon in Regional Ecosystems Program (K.D. Hyatt); Fertilizer has been supplied by DFO

Lake Enrichment Program (D. MacKinlay) and by Canfor. Field assistance was provided by Henry Nelson, Bert Svanvik, Phil Alfred and other support staff from the Gwa'ni Hatchery. Assistance is also provided by the Nimpkish Resource Management Board and Doug McCorquodale (Stewardship Coordinator 2000-2002), the 'N̄am̄gis First Nation, and Canfor. Field and laboratory work are conducted by Barry Hanslit (DFO), Leila Hanslit (Northwest Ecosystems Associates), Stan Sutey (Accipiter Fish and Wildlife) and Elaine Carney.