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Judy Reservoir Monitoring Project 2009–2010 Final Report

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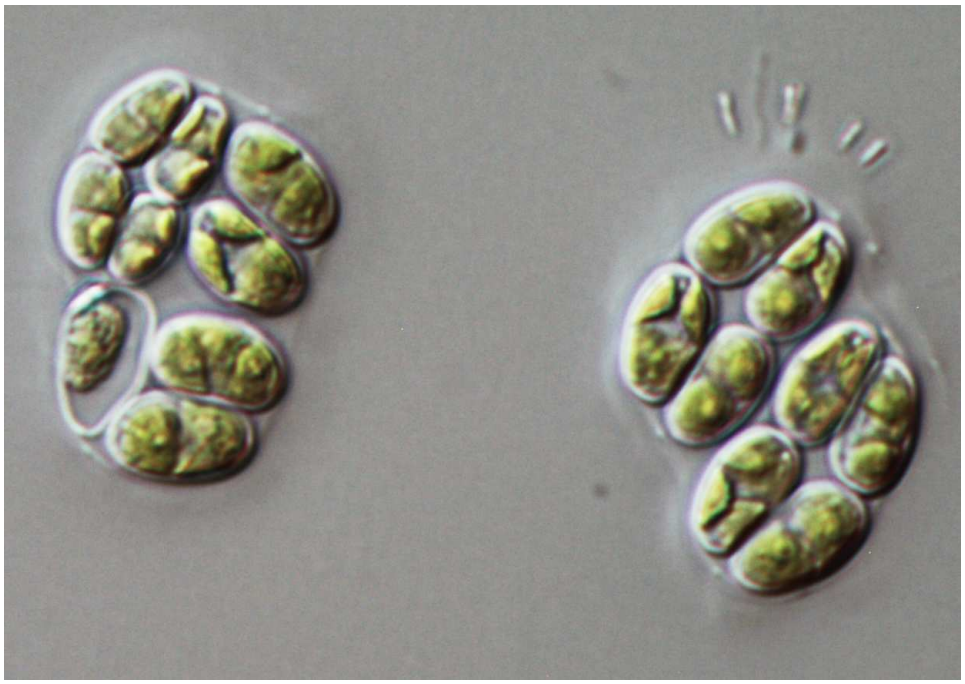

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2009–2010 Final Report

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We thank Marilyn Desmul, Jessie Rosanbalm, and Kate Lewis for assistance with the project

Contents

Introduction

The purpose of this study was to identify and count the phytoplankton in water samples collected from Judy Reservoir, and measure other standard biological and chemical parameters. Water quality data and algae counts have been collected on a weekly basis since October 2006; annual data summaries were sent to the Skagit Public Utility District No. 1 in 2007, 2008, and January 2010.

As part of our monitoring contract, we have provided weekly chemistry data and algal cell counts to the Public Utility District #1 of Skagit County. Because we now have multi-year data set, this year's annual report will include a description of the data collected from October 2006 through October 2010. The data will be described in a series of annotated figures, beginning on page 5. Appendix A, beginning on page 22, contains an updated photographic record of our calculations for estimating algal biovolume. Appendix B, beginning on page 56, contains updated tables of the data that include all corrections and revisions to the data set, including biovolume estimates for most types of algae.

Methods

Skagit Public Utility District No. 1 personnel collected water samples from the pump house at Judy Reservoir once a week from October 26, 2006 through October 25, 2010. The samples were shipped on ice by courier to the Institute for Watershed Studies laboratory the same day.

Samples for chlorophyll a were collected in amber polyethylene bottles, transported on ice, then measured in the lab using a fluorometer and an acetone extraction as described by Standard Method 10200 H. (APHA, 2005). Samples were measured in duplicate and the mean was reported.

Samples for total phosphorus and total nitrogen analyses were collected in 500 mL acid-washed polyethylene bottles.[1] The samples were preserved upon arrival in the laboratory then measured by methods as described in Table 1.

[1]Turbidity, nitrate, and soluble phosphorus were also measured from October 26, 2006 through October 1, 2007.

Samples for phytoplankton identification were collected in polyethylene bottles and preserved with Lugol's solution as described in Standard Method 10200 A. (APHA, 2005) until microscopic analysis. During the first year of monitoring, an improved method of concentrating the algae samples was introduced, which resulted in a two month overlap when both methods were used.

The original method was used on samples collected from October 26, 2006 through May 16, 2007. Algae were concentrated by filtering the sample through 20 μm Nitex mesh and counted using a Palmer counting cell. This method can miss cells smaller than 10–20 μm, so we adopted a revised method that uses a settling chamber to retain all cells. Beginning in March 2007, samples were counted using a 25-, 50- or 100-mL settling chamber.[2] Counts were made using a compound microscope at 200x or 400x. Multiple fields were counted on each slide, with the number of fields being determined by cell density.

Algal biovolume calculations were made following the procedures outlined by EPA (2008). When possible, at least 10 photographs were taken of each algal species identified from the site.[3] The images were calibrated using a stage micrometer and biovolume was estimated based on a representative geometric shape (e.g., ovoid, sphere, rectangle). To estimate phytoplankton biovolume, the weekly species counts were multiplied by the corresponding average biovolume for that species.

[2] Samples were counted using both methods from March through May 2007.

[3] Algal species that were too rare to provide at least 10 images were omitted from the biovolume calculations. This has little effect on biovolume because the species represent a small fraction of the total count.

Analyte	Abbr.	Method Reference (APHA 2005)	Detection Limit/ Sensitivity
Algae counts (Oct 2006 - May 2007)	NA	APHA 10200 C. Membrane filtration†	NA
Algae counts (Mar 2007 - Oct 2008)	NA	APHA 10200 C. Sedimentation	NA
Algae biovolume	NA	EPA LG401, Rev. 03	NA
Chlorophyll - lab	Chl	SM10200 H, acetone extraction	$\pm$0.1 mg/m^3
Nitrogen - nitrate/nitrite	NO_3	SM4500-NO3 I., flow inject, Cd reduction	10 μg NO_3-N/L
Nitrogen - total	TN	SM4500-NO3 I., flow inject, persulfate digest	10 μg N/L
Phosphorus - orthophosphate	OP	SM4500-P G., flow inject	3 μg PO_4-P/L
Phosphorus - total	TP	SM4500-P G., flow inject, persulfate digest	5 μg P/L
Turbidity	Turb	SM2130, nephelometric	$\pm$0.2 NTU

*Fecal coliform analyses were provided by Edge Analytical, 805 Orchard Dr., Bellingham, WA.

Table 1: Summary of analytical methods used by the Institute for Watershed Studies in the Judy Reservoir monitoring project.

References

APHA, 2005. Standard Methods for the Examination of Water and Wastewater, 21st Edition. American Public Health Association, American Water works Association, and Water Environment Federation, Washington D. C.

Carlson, R E. and J. Simpson. 1996. A Coordinator's Guide to Volunteer Lake Monitoring Methods. North American Lake Management Society. 96 pp.

EPA, 2008. LG401 - Standard Operating Procedure for Phytoplankton Analysis, Revision 03, February 2003. Chapter 4: Biological Parameters in *Sampling and analytical procedures for Great Lakes National Program Office (GLNPO) Open Lake Water Quality Survey of the Great Lakes*, online report at http://www.epa.gov/glnpo/monitoring/procedures/sop2007/Ch4/LG401-070130.pdf

Annotated Figures

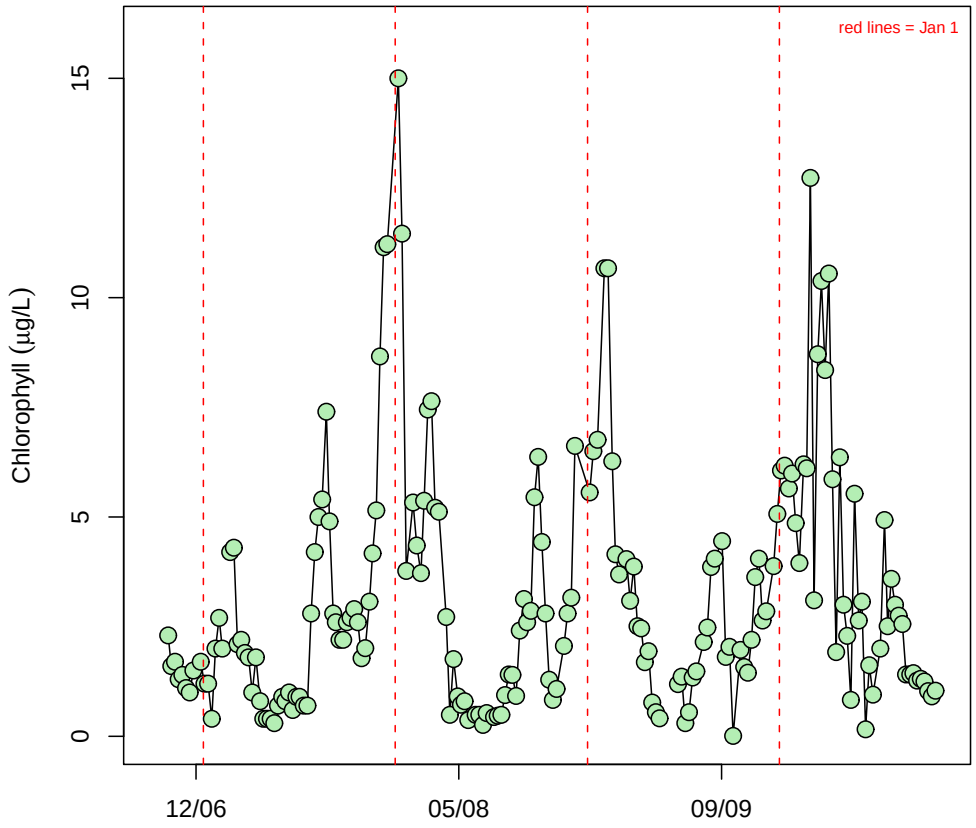
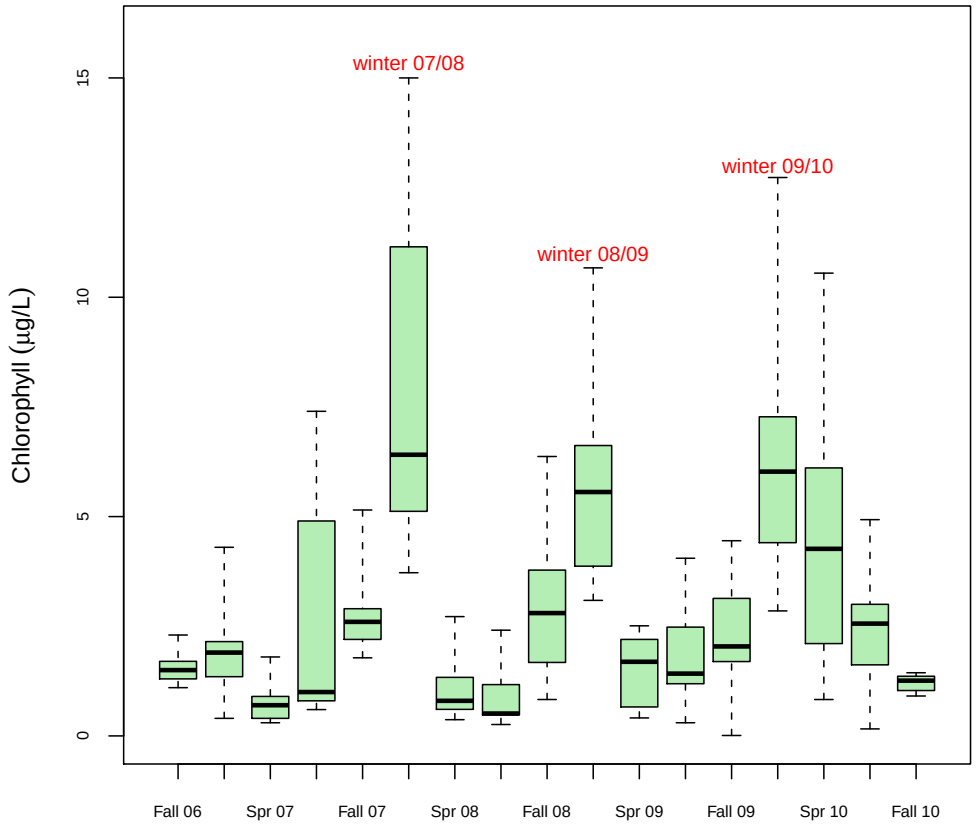
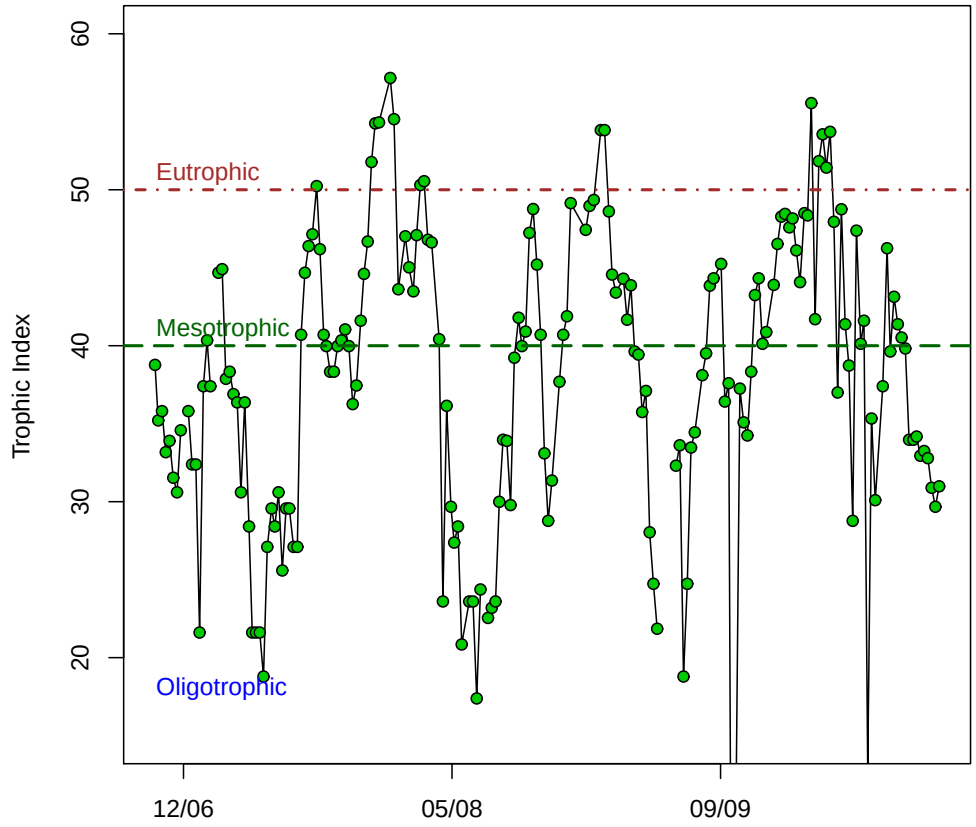


Figure 1: Chlorophyll levels in Judy Reservoir (October 2006 – October 2010). Chlorophyll is the primary photosynthetic pigment in algal cells, and is generally the best indicator of the amount of algae present in a water sample. In most lakes, chlorophyll levels are higher during the summer and fall compared to the winter and spring, coinciding with summer/fall algal blooms. In Judy Reservoir, the chlorophyll concentrations were often high during the winter (see Figure 2), which is unusual because algae populations usually decline during the winter.



Spring = April-May Summer = June-August Fall = September-November Winter = December-March

Figure 2: Boxplot showing the range of chlorophyll concentrations by season in Judy Reservoir (October 2006 – October 2010). The boxes show the median (center line) and enclose the upper/lower 25% quartiles; the dashed lines show the minimum/maximum values for each season. The extremely high winter chlorophyll levels were unexpected; the moderately high levels in the fall are similar to what has been observed in other regional lakes and reservoirs. The 2007/2008 and 2008/2009 winter peaks appear to have been caused by chrysophyte blooms; the chrysophyte density was lower in the winter of 2009/2010 (Figure 10).



$$\mathrm{TSI_{chl}} = 9.81\ (\ln \mathrm{chl}) + 30.6$$

Figure 3: Carlson's trophic state index ($\mathrm{TSI_{chl}}$) for Judy Reservoir (October 2006 - October 2010). Carlson's $\mathrm{TSI_{chl}}$ is often used to classify lakes based on biological productivity (Carlson and Simpson, 1966). Productive or *eutrophic* lakes have high TSIs ($\geq$50); unproductive or *oligotrophic* lakes have low TSIs ($\leq$40); lakes falling between these ranges are labeled *mesotrophic*. Trophic state is usually measured during the summer, or whenever algae populations are expected to be high. In Judy Reservoir, some of the highest TSIs occurred during the winter because the index is calculated using chlorophyll levels. During most of the year, the $\mathrm{TSI_{chl}}$ was fairly low, with the median falling at the boundary between mesotrophic and oligotrophic (median $\mathrm{TSI_{chl}} = 39$).

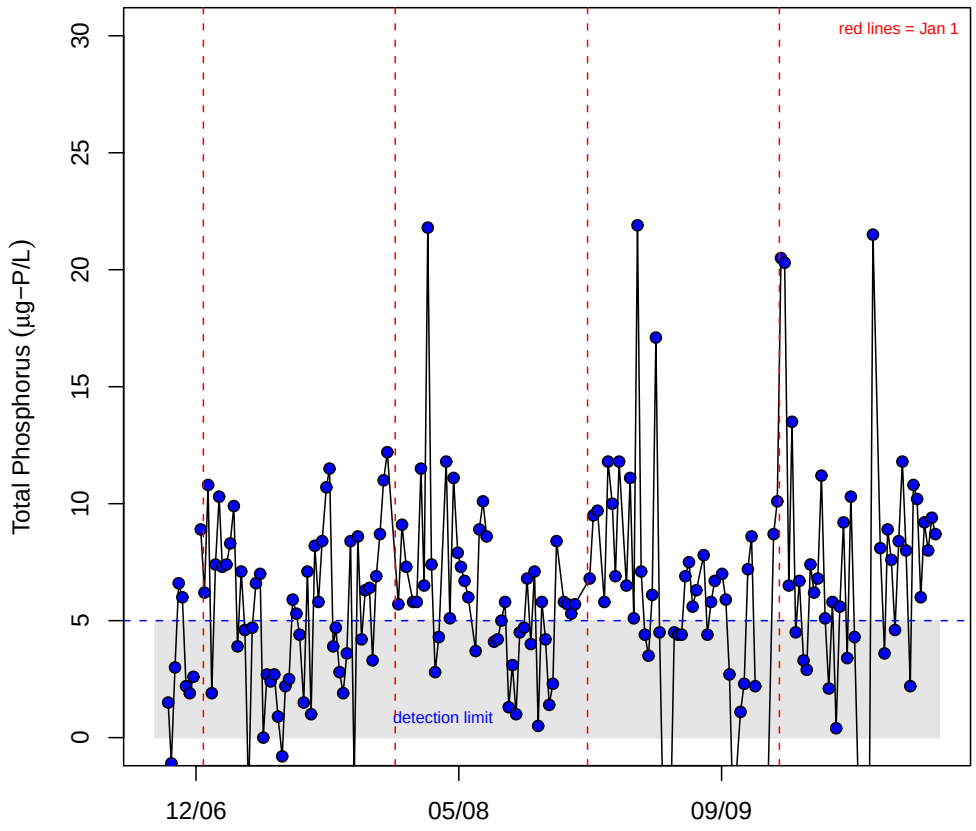


Figure 4: Total phosphorus concentrations in Judy Reservoir (October 2006 - October 2010). Total phosphorus includes organic phosphorus (phosphorus associated with algae and other biota) and dissolved phosphorus (primarily soluble orthophosphate). Phosphorus is an important nutrient for algae, and is generally considered the nutrient that limits the amount of algae in a lake. The average total phosphorus concentration in Judy Reservoir was only 5.9 μg-P/L (barely above the detection limit of 5 μg-P/L), and all but six of the 192 samples were $<$15 μg-P/L. Given the relatively high chlorophyll levels that occur in the reservoir, the low phosphorus is surprising; however, algae are very efficient at extracting this nutrient from the water column.

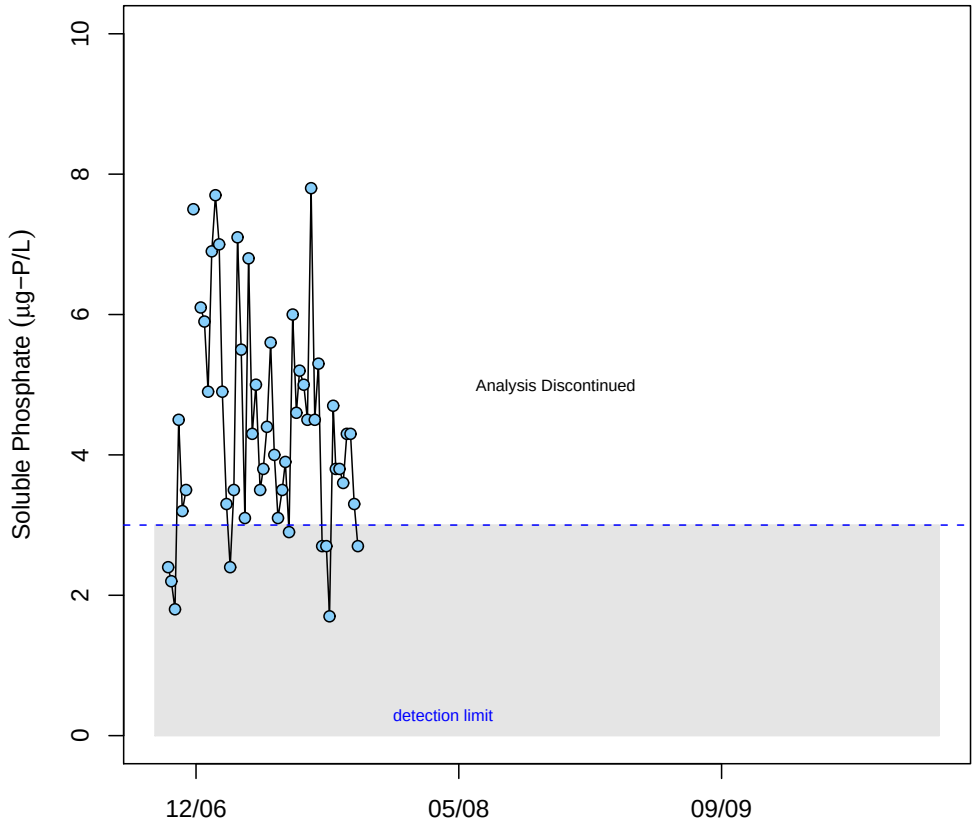


Figure 5: Soluble orthophosphate concentrations in Judy Reservoir (October 2006 - October 2007). This analysis was only done during the first year of the project. Soluble orthophosphate is the inorganic portion of total phosphorus, and total phosphorus is generally a better predictor of algal densities. Correlation analysis* indicated that there was a statistically significant relationship between total phosphorus and chlorophyll concentrations (Kendall's τ = 0.24, p-value = 0.000037), but no significant relationship between soluble orthophosphate and chlorophyll (τ = -0.13; p-value = 0.1968).

*Correlation analysis measures the strength of the relationship between two variables. Correlation test statistics range from -1 to +1; the closer to $\pm$1, the stronger the correlation. The significance is measured using the p-value; significant correlations have p-values $<$0.05.

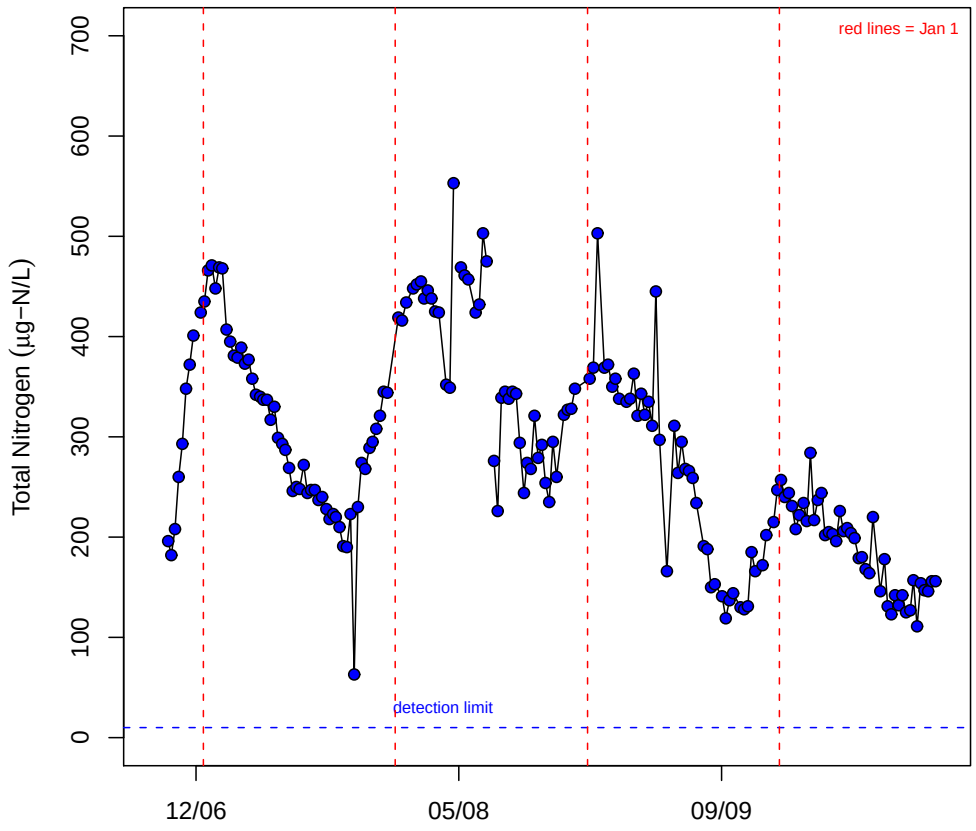


Figure 6: Total nitrogen concentrations in Judy Reservoir (October 2006 - October 2010). Total nitrogen represents the combined concentrations of organic nitrogen (nitrogen associated with algae and other biota) and dissolved inorganic nitrogen (nitrate, nitrite, and ammonium). In Judy Reservoir, about half of the total nitrogen was inorganic (average $\frac{NO_3}{TN} = 0.52$). Algae use inorganic nitrogen for growth, so it is common to see depletion of total nitrogen and nitrate during the summer (see Figure 7). Nitrogen rarely limits total algal growth because cyanobacteria can convert dissolved nitrogen gas (N_2) into inorganic nitrogen. Low concentrations of inorganic nitrogen will, however, limit the growth of certain types of algae and favor the growth of cyanobacteria.

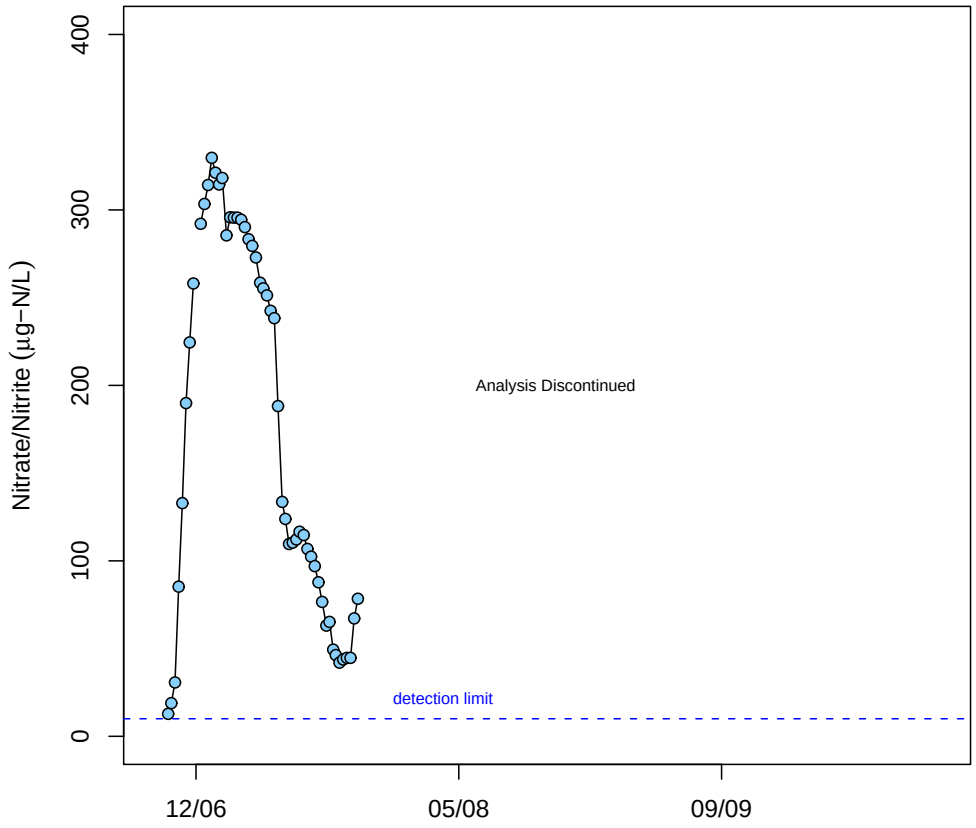


Figure 7: Nitrate/nitrite concentrations in Judy Reservoir (October 2006 - October 2007). This analysis was only done during the first year of the project. Nitrate and nitrite are often measured simultaneously; nitrite concentrations are usually negligible in lake samples, so the majority of nitrogen in the sample will be nitrate. There was an excellent correlation between nitrate/nitrite and total nitrogen in the samples (τ = 0.88; p-value $<$0.00001), and the nitrate/nitrite concentrations followed the same seasonal pattern as the total nitrogen data.

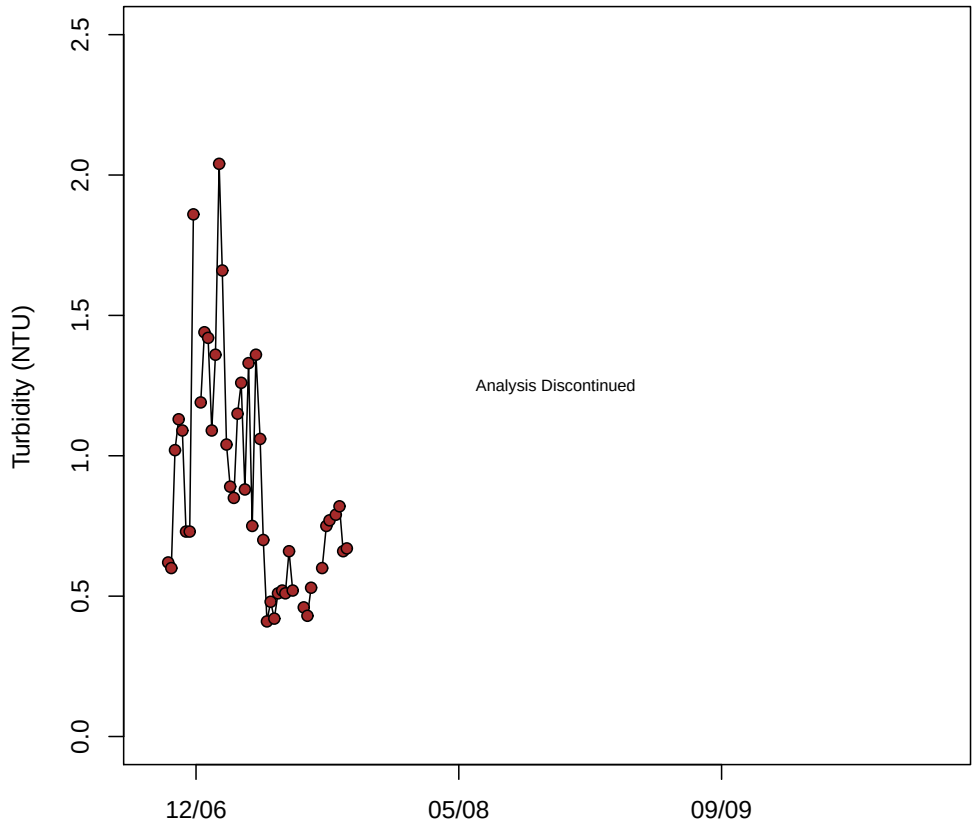


Figure 8: Turbidity levels in Judy Reservoir (October 2006 - October 2007). This analysis was only done during the first year of the project. Turbidity is a measurement of the clarity of a water sample. Algal blooms usually increase turbidity, but so will suspended sediments from lake turbulence or storm runoff. There was a weak but significant correlation between turbidity and chlorophyll levels (τ = 0.25; p-value = 0.0178).

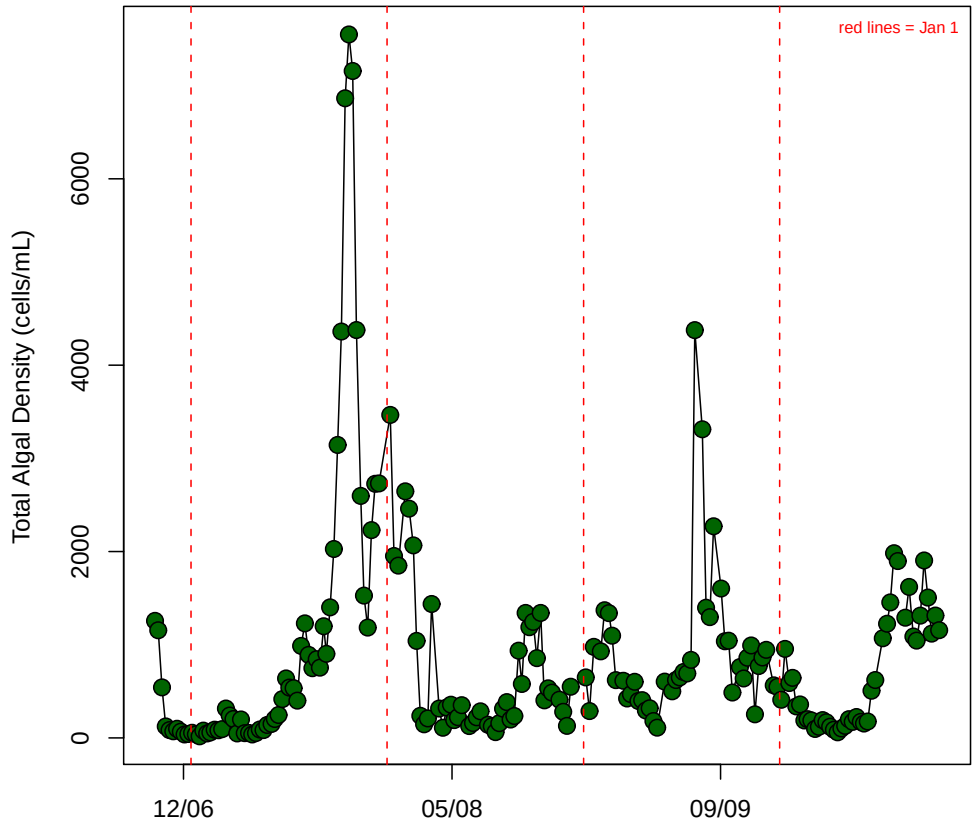


Figure 9: Total algal density (October 2006 - October 2010). Algal density is determined by settling a known volume of Judy Reservoir water that has a small amount of Lugol's iodine preservative added to kill and stain the algae. The highest algal counts usually occurred from summer to late fall, which is typical for local lakes. Algal counts were sometimes high during the winter (December-February), which is unusual for most lakes, but was consistent with occasional high winter chlorophyll concentrations (Figure 1).

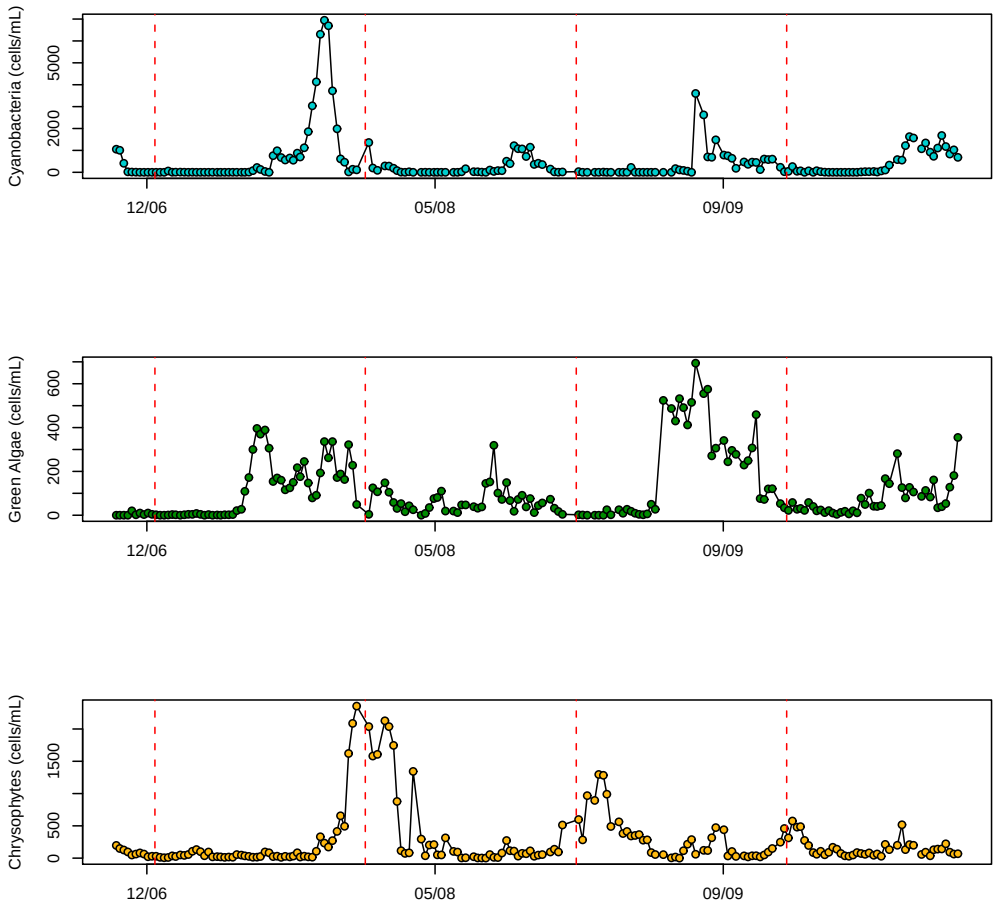


Figure 10: Density of cyanobacteria, green algae, and chrysophytes (October 2006 - October 2010). These three types of algae dominated the counts in Judy Reservoir. Cyanobacteria (bluegreen "algae") typically bloom during fall, and were especially dense in October 2007. Green algae had rather erratic counts, but were usually higher during the summer and fall. The chrysophyte counts were very high during the winter/spring of 2007/2008, and moderately high during the winter/spring of 2008/2009. Chrysophytes often bloom during the early spring, so the winter peaks were only a little earlier than expected.

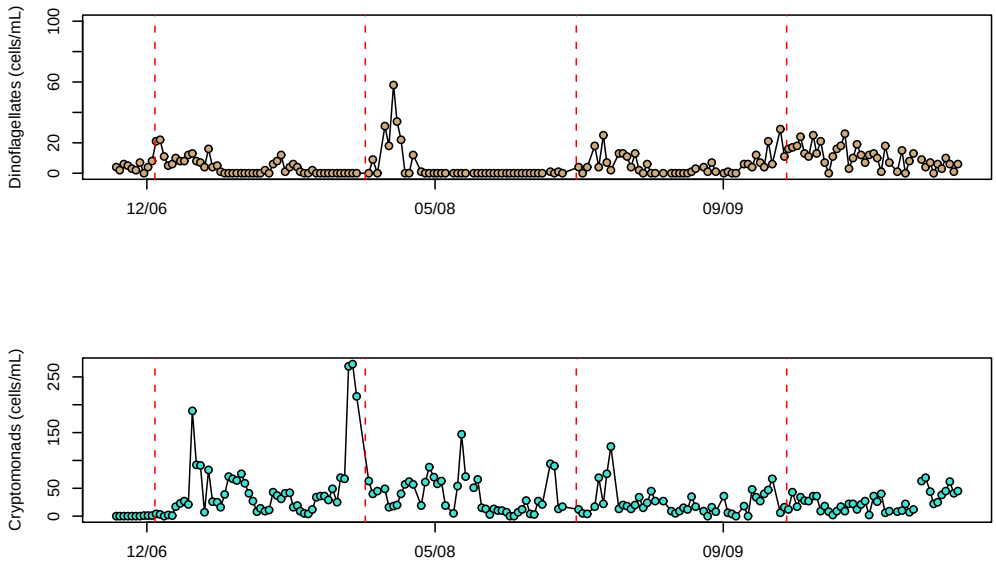


Figure 11: Density of dinoflagellates and cryptomonads (October 2006 - October 2010). These two groups of algae are never very abundant (note scale difference in this figure compared to Figure 10), but the species that are present in Judy Reservoir are often large in size. As a result, they may contribute disproportionally to the algal biovolume or chlorophyll measurements.

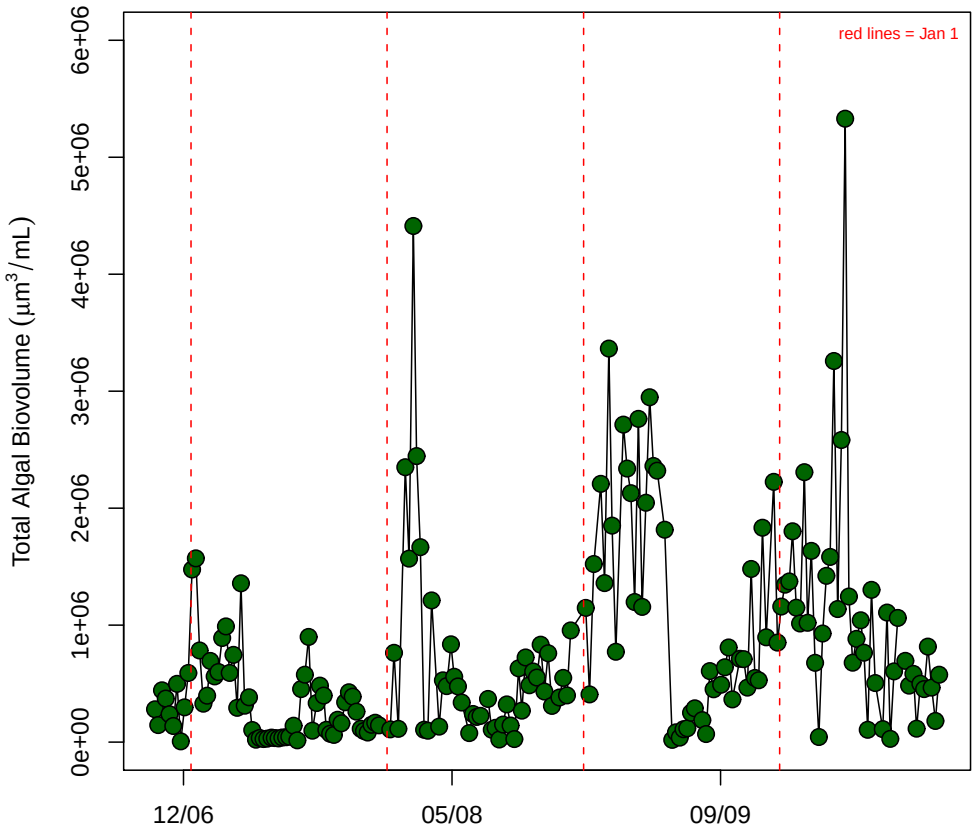


Figure 12: Total algal biovolume (October 2006 - October 2010). Freshwater algae range in size from very tiny ($<$2 μm diameter) to large enough to see without magnification ($>$1 mm diameter). Algal biovolume is calculated by measuring the size of the algal cell, calculating the volume occupied by that cell, then multiplying the individual "biovolume" by the number of algal cells in the sample. Biovolume estimates are not available for all species in Judy Reservoir because we need a minimum of 10 good photographs per species. As additional cell measurements become available, we will provide updated biovolume estimates.

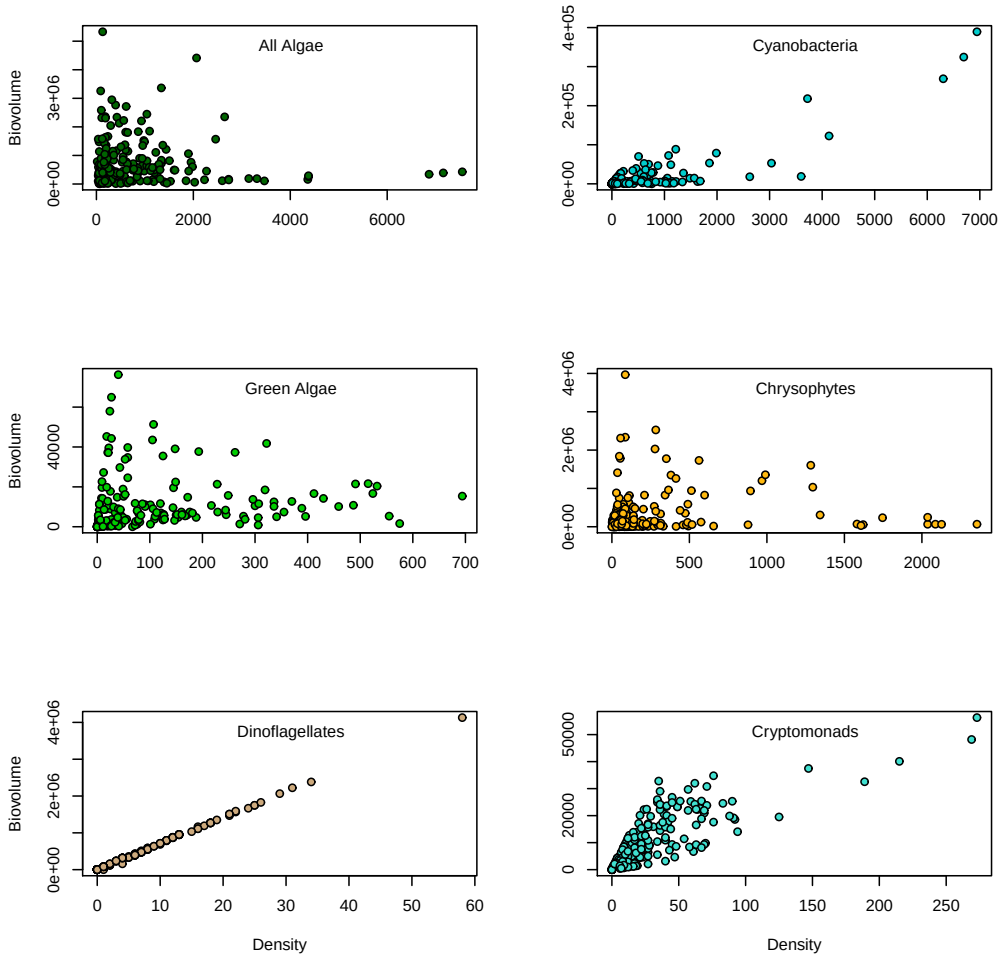


Figure 13: Relationship between algal cell counts (density) and algal biovolume. Because of the variation in cell sizes between different algal species, biovolume is calculated separately for each species. This figure illustrates how variation in cell size affects biovolume. If all of the species in a sample are approximately the same size, the relationship between density and biovolume is nearly linear (e.g., Dinoflagellates). If, however, the sample contains species that are very different in size, as is the case for green algae and chrysophytes, there is little relationship between density and biovolume. Some types of algae, like the cyanobacteria, have many species present in the sample, but the different species have somewhat similar cell shapes and sizes. The cryptomonads are interesting because there are only a few species present, and the cells are all basically the same shape (ovals), but they range from tiny to quite large in size.

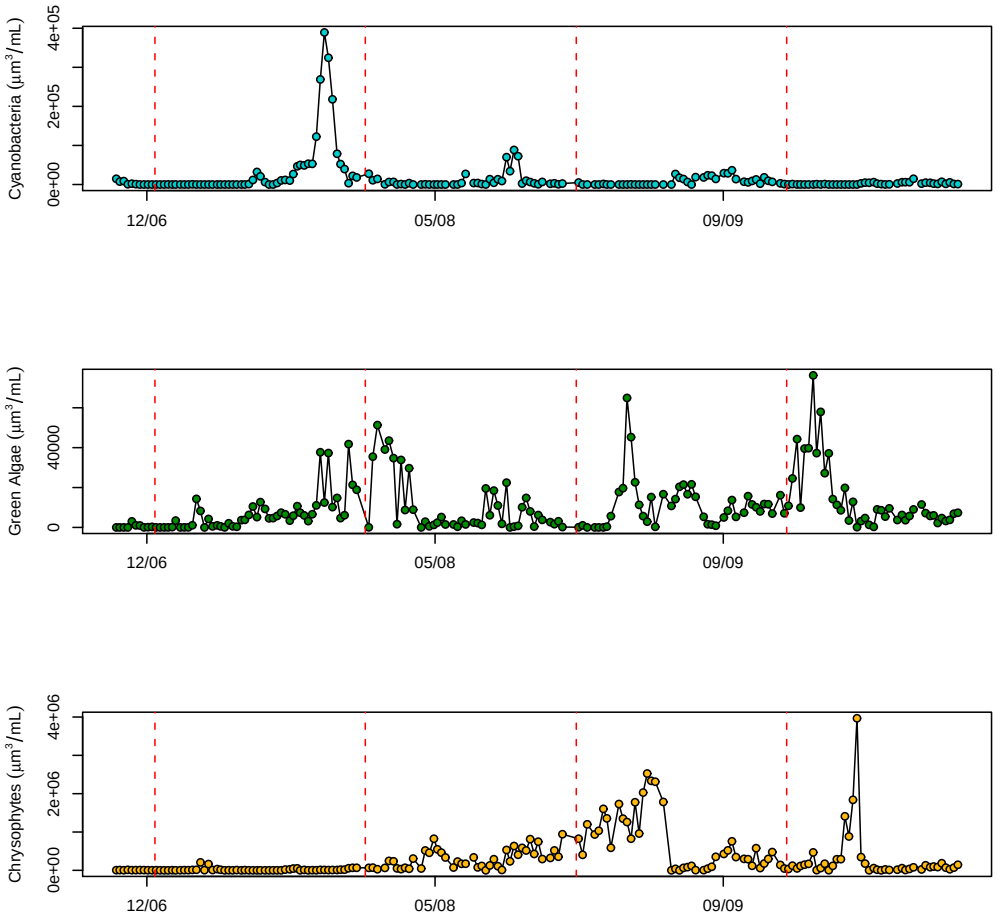


Figure 14: Biovolume of cyanobacteria, green algae, and chrysophytes (October 2006 - October 2010). These three types of algae usually dominate the biovolume estimates. Several important species that are common in the numerical counts do not yet have biovolume measurements. These include two large colonial species (*Woronichinia* - cyanobacteria; *Botryococcus* - green algae) and four common diatoms (*Asterionella*, *Cyclotella*, *Navicula*, and *Surirella*). Adding biovolume estimates for these six species may change the biovolume patterns in this figure.

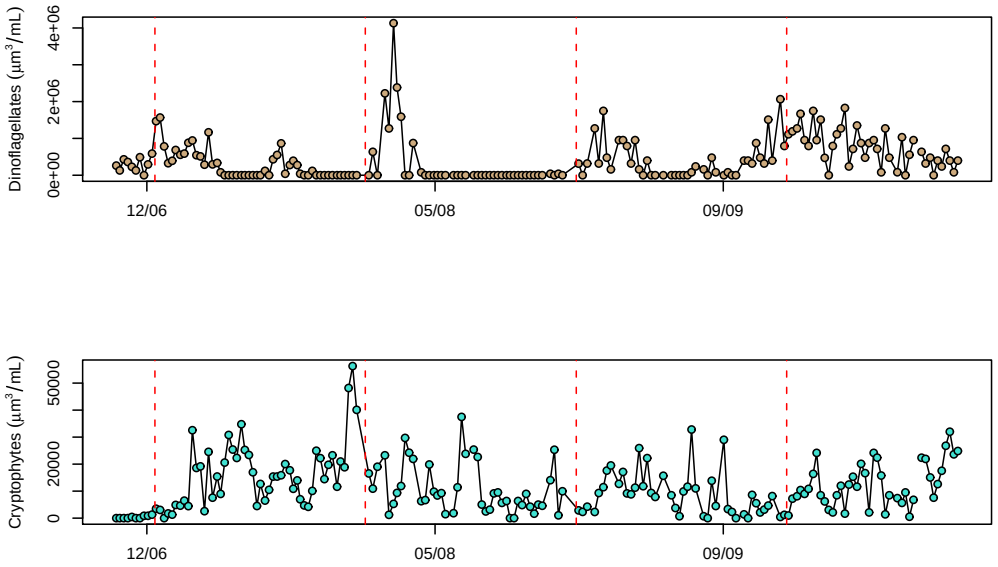


Figure 15: Biovolume of dinoflagellates and cryptomonads (October 2006 - October 2010). Cryptomonads (lower plot) are rarely common in the Judy Reservoir samples, so they rarely contribute much to algal biovolume estimates. Dinoflagellates occasionally form blooms in the reservoir, and because the dinoflagellate cells are quite large, when blooms occur the dinoflagellate biovolume is very high.

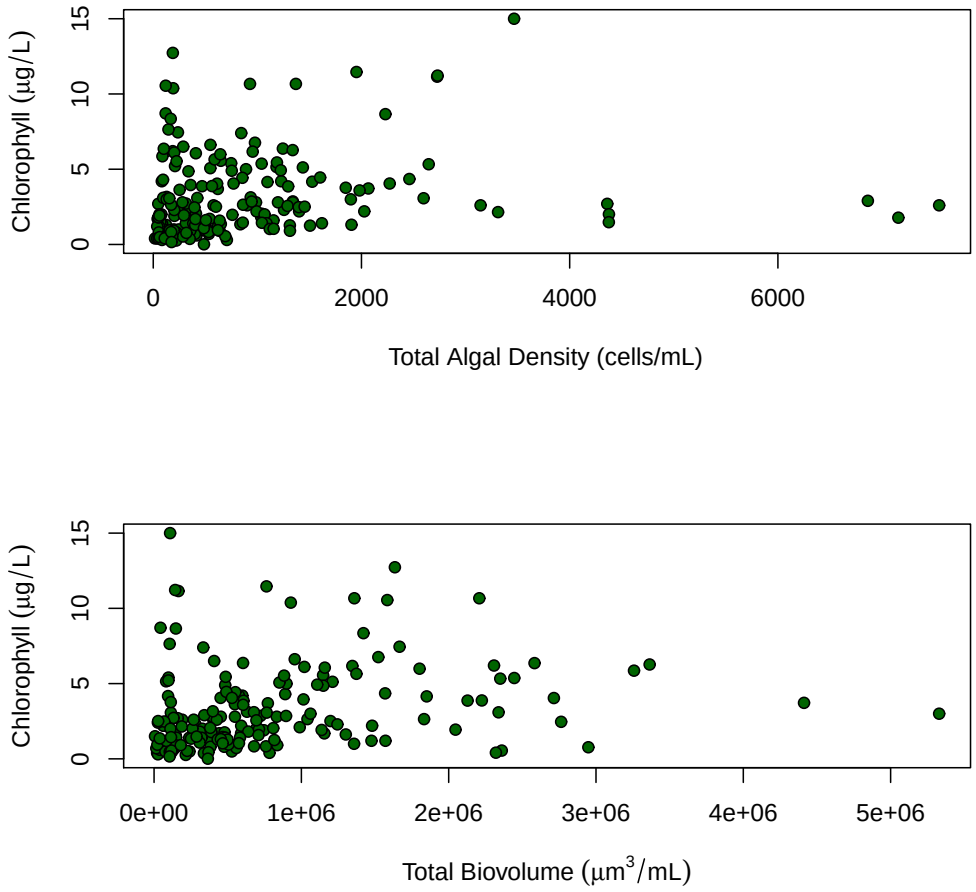


Figure 16: Relationship between chlorophyll, total biovolume, and total density in Judy Reservoir algae. Algal counts, algal biovolume, and algal chlorophyll levels are related, but each measurement tells you something slightly different about the amount of algae in the reservoir, so it is not surprising that these plots show a high degree of scatter when the different measurements are plotted against each other. Numerical counts show general patterns in algal population dynamics. For example, the Judy Reservoir counts revealed unusually high winter densities of chrysophytes (Figure 10). Chlorophyll measurements are fast, inexpensive, and are commonly used to indicate trophic state (Figure 3), but don't indicate which species are causing problems. Algal biovolume is the most direct measurement of the "weight" of algae in the sample, but needs to be measured for each species separately. Because biovolume estimates differentiate between large and small cells, the data can be used to identify which algae are causing problems (e.g., the magnitude of dinoflagellate blooms).

A Plankton Images

This appendix contains photographic images and biovolume equations for phytoplankton in Judy Reservoir. Biovolume calculations require measurements from a minimum of ten cells, so only moderately common taxa are used for biovolume estimates.

Cyanobacteria (bluegreen algae)		Green algae	
Anabaena flos-aquae	●	*Ankyra*	○
Aphanocapsa	●	*Botryococcus*	○
Chroococcus dispersus	●	*Chlamydamonas*	○
Chroococcus limneticus	○	*Cosmarium*	●
Chroococcus turgidus	●	*Crucigenia*	●
Gloeocapsa	●	*Crucigeniella*	○
Microcystis	●	*Dictyosphaerium*	●
Unidentified bluegreen	●	*Elakatothrix*	●
Woronichinia	○	*Eudorina*	●
		Gloeocystis	●
Golden algae		*Oocystis*	●
Dinobryon bavaricum	●	*Scenedesmus*	●
Dinobryon sertularia	●	*Selenastrum*	●
Mallomonas	●	*Sphaerocystis*	○
Synura petersenii	●	*Spondylosium*	●
Synura uvella	●	*Staurastrum*	○
Unidentified golden	●	*Tetraedron*†	○
Uroglena	●		●
Asterionella (diatom)	○	Dinoflagellates	
Aulacoseira (diatom)	●	*Ceratium hirudinella*	●
Cyclotella (diatom)	○	*Gymnodinium*	●
Navicula (diatom)	○	*Peridinium*	○
Stephanodiscus (diatom)	●		
Surirella (diatom)	○	Cryptomonads	
Synedra (diatom)	●	*Cryptomonas*	●
Tabellaria (diatom)	●	*Komma/Chroomonas*	●
Unidentified diatoms	○		

†Taxonomic revisions may result in moving this genus to a different group

Table 2: List of algae collected in Judy Reservoir, October 2006 - October 2010. Algae with density measurements are identified using an open circle (○); algae that also have biovolume measurements are identified using a solid circle (●).

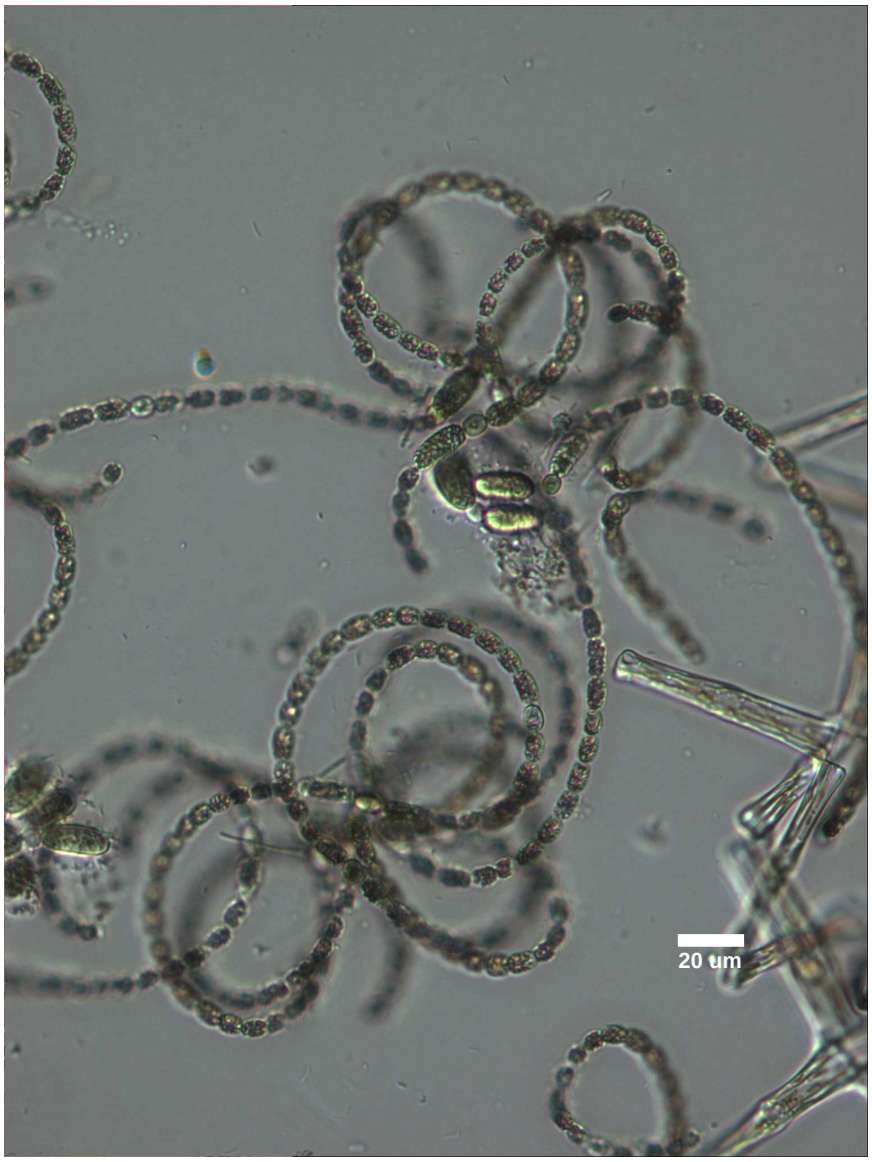


Figure 17: *Anabaena flos-aquae* (cyanobacteria).

$$\text{Ovoid biovolume} = \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right)$$

$$\begin{aligned}
\text{Avg. width} &= 6.07\,\mu\text{m} \\
\text{Avg. length} &= 7.97\,\mu\text{m} \\
\text{Avg. biovolume} &= 159.3\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 124.1 - 194.5\,\mu\text{m}^3
\end{aligned}$$

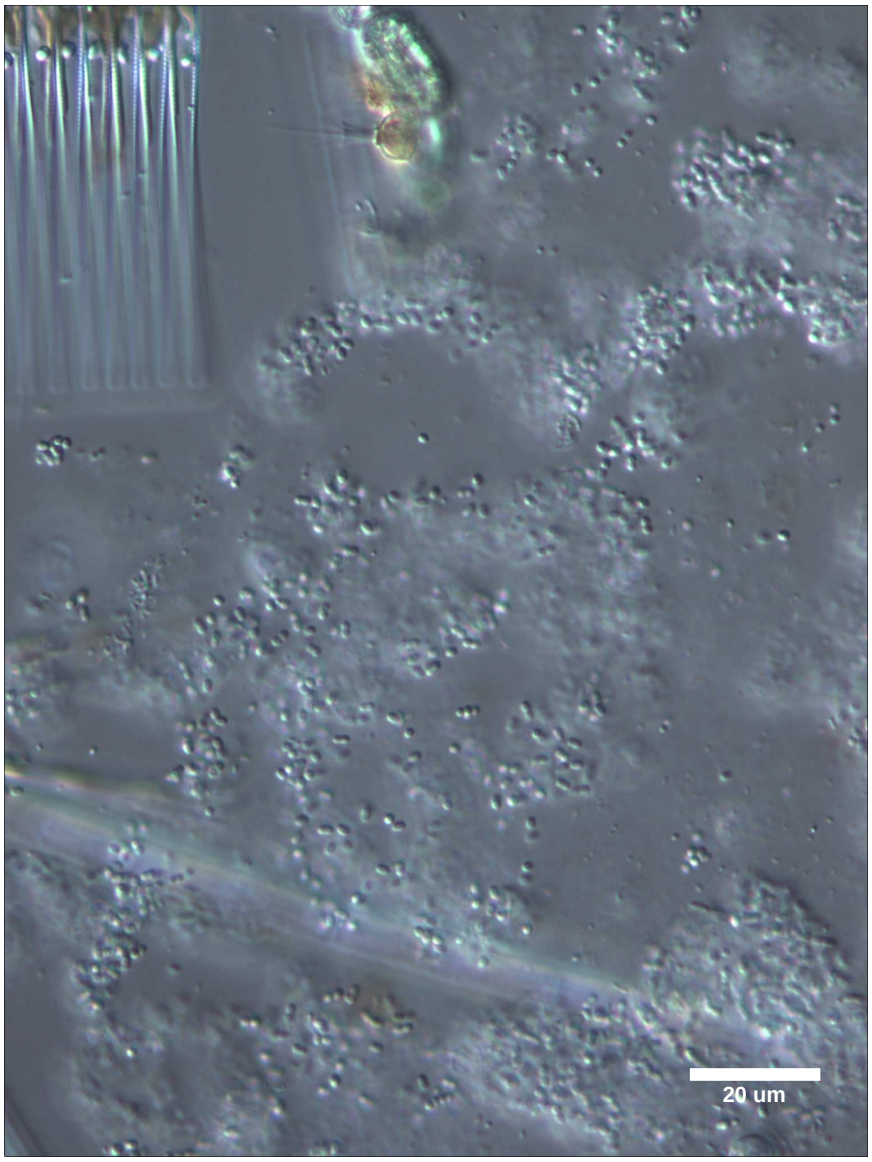


Figure 18: *Aphanocapsa* (cyanobacteria).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 1.34\,\mu\text{m} \\
\text{Avg. length} &= 1.54\,\mu\text{m} \\
\text{Avg. biovolume} &= 1.50\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 0.96 - 2.03\,\mu\text{m}^3
\end{aligned}$$

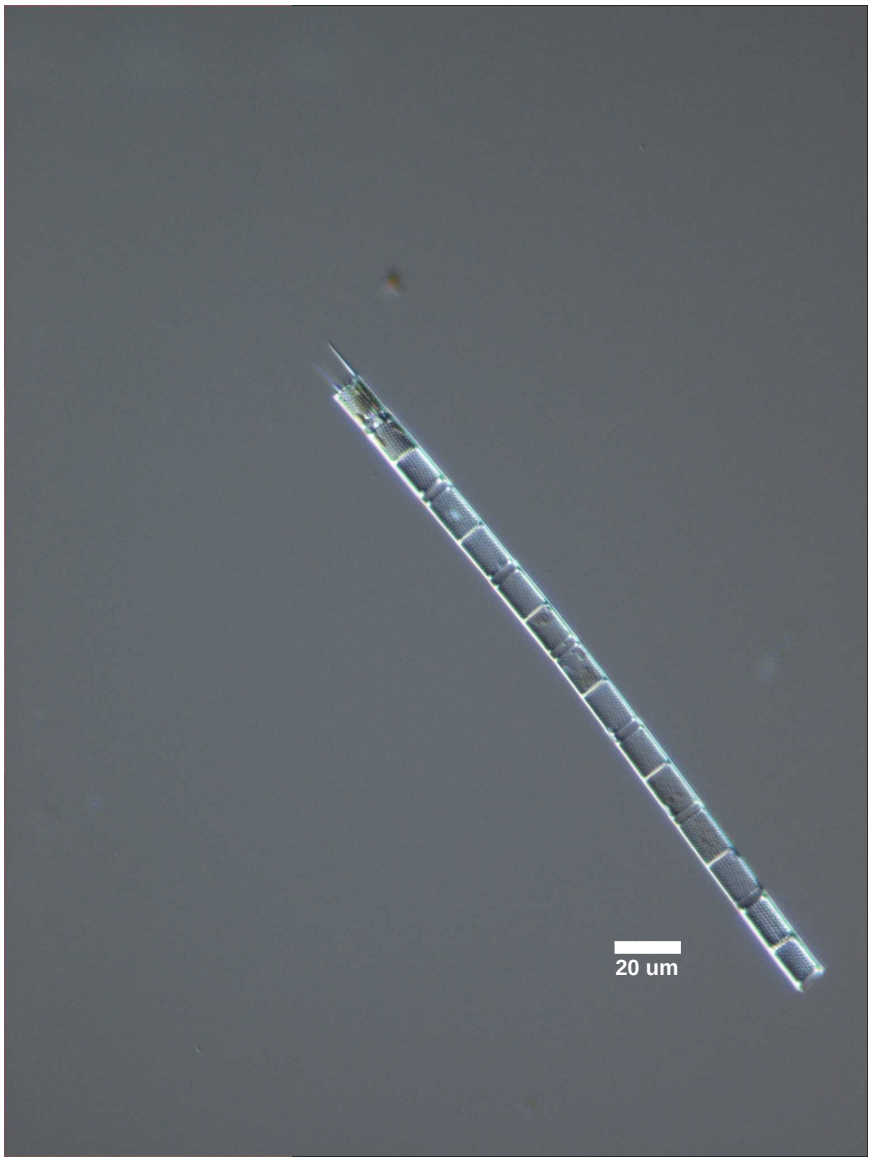


Figure 19: *Aulacoseira* (diatom).

$$\text{Cylinder biovolume} = \pi \times \left(\frac{\text{width}}{2}\right)^2 \times \text{length}$$

$$\begin{aligned} \text{Avg. width} &= 6.6\,\mu\text{m} \\ \text{Avg. length} &= 29.0\,\mu\text{m} \\ \text{Avg. biovolume} &= 1,033\,\mu\text{m}^3 \\ \text{Biovolume 95\% CI} &= 769 - 1,296\,\mu\text{m}^3 \end{aligned}$$

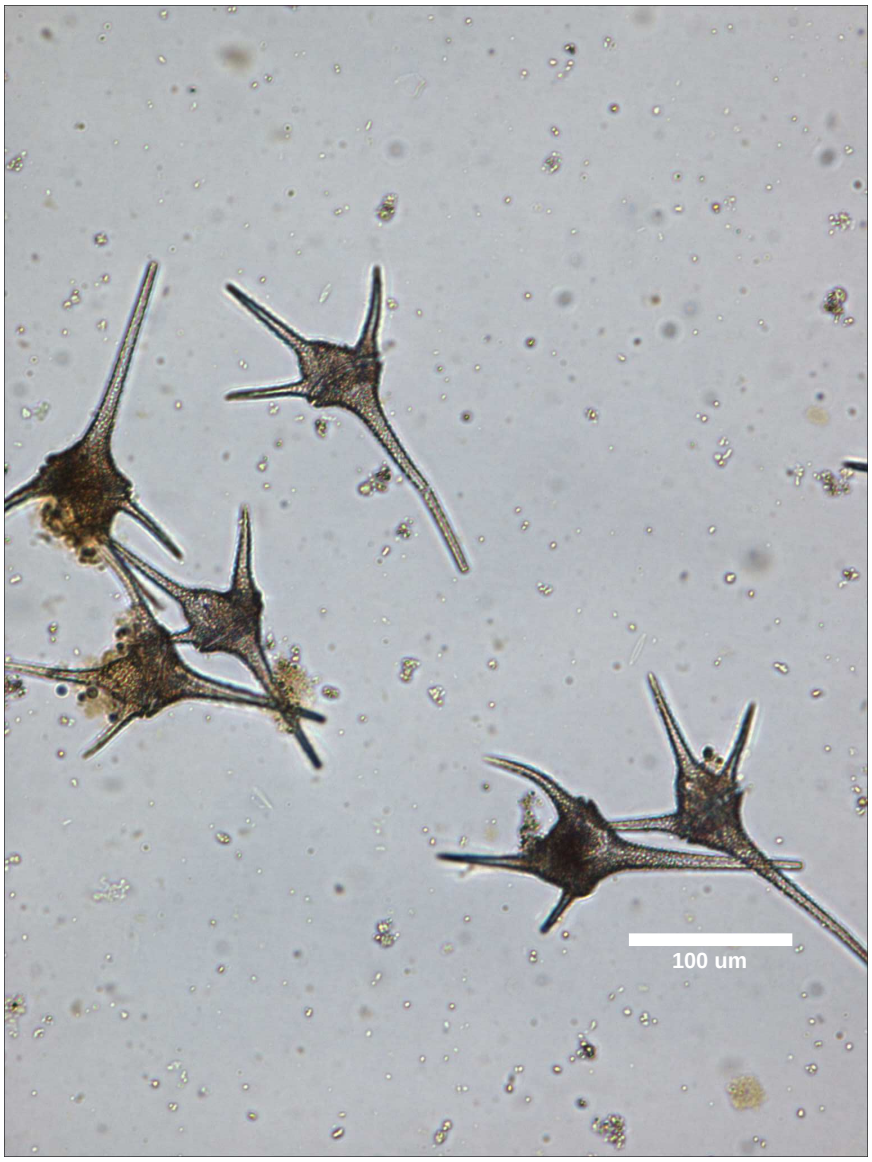


Figure 20: *Ceratium hirundinella* (dinoflagellate).

$$\text{Ceratium biovolume} = \left(\frac{4}{3}\pi \times \left(\frac{\text{diameter}}{2}\right)^2 \times \text{length}\right) + \left(\pi \left(\frac{\text{width}}{2}\right)^2 \times \text{depth}\right)$$

$$\begin{aligned}
\text{Avg. width} &= 44.3\,\mu\text{m} \\
\text{Avg. length} &= 52.4\,\mu\text{m} \\
\text{Ave. depth} &= 43.2\,\mu\text{m} \\
\text{Ave. diameter} &= 9.4\,\mu\text{m} \\
\text{Avg. biovolume} &= 72,215\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 61,334 - 83,096\,\mu\text{m}^3
\end{aligned}$$

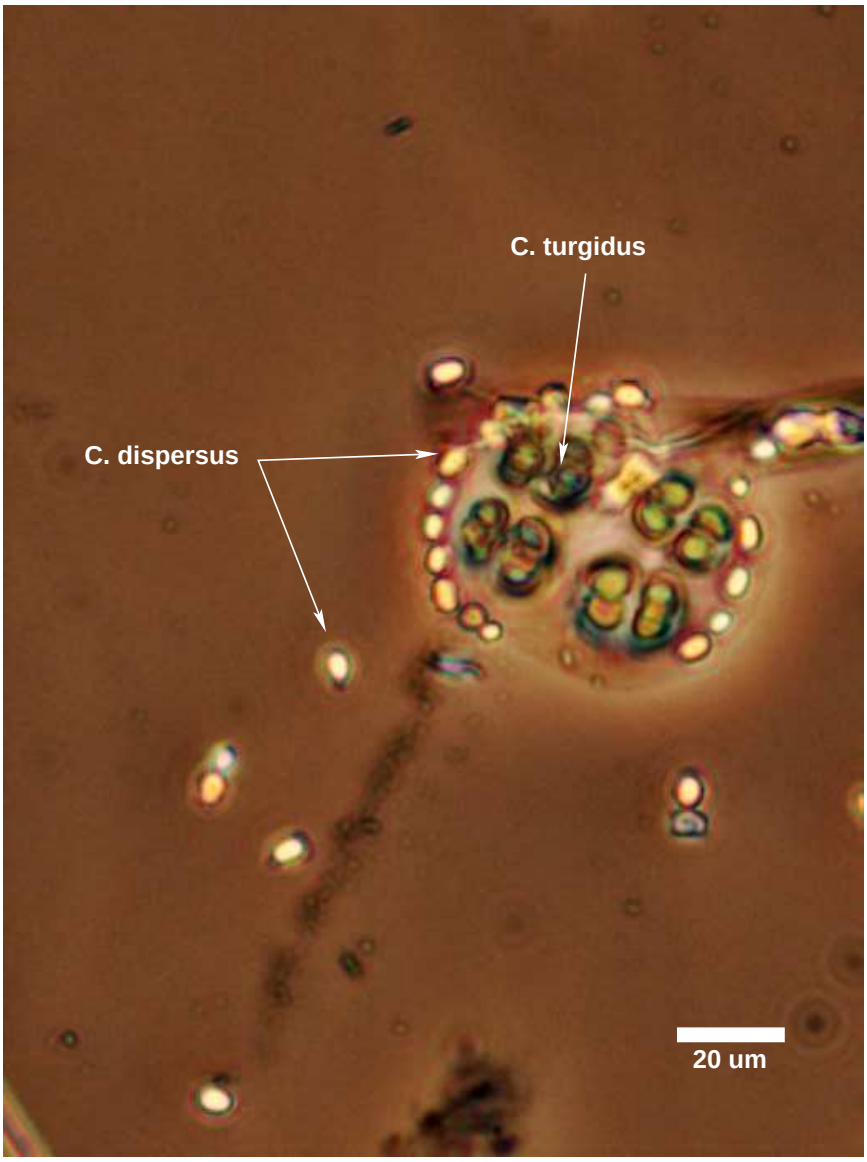


Figure 21: *Chroococcus dispersus* (cyanobacteria)

$$\text{Ovoid biovolume} = \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right)$$

$$\begin{aligned}
\text{Avg. width} &= 1.52\,\mu\text{m} \\
\text{Avg. length} &= 2.20\,\mu\text{m} \\
\text{Avg. biovolume} &= 2.95\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 2.26 - 3.64\,\mu\text{m}^3
\end{aligned}$$

Figure 22: *Chroococcus turgidus* (cyanobacteria)

$$\text{Ovoid biovolume} = \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right)$$

$$\begin{aligned}
\text{Avg. width} &= 6.52\,\mu\text{m} \\
\text{Avg. length} &= 7.22\,\mu\text{m} \\
\text{Avg. biovolume} &= 187.5\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 143.0 - 232.1\,\mu\text{m}^3
\end{aligned}$$

Figure 23: *Cosmarium* (green algae - desmid).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 15.11\,\mu\text{m} \\
\text{Avg. length} &= 15.39\,\mu\text{m} \\
\text{Avg. biovolume} &= 1,866\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 1,535 - 2,197\,\mu\text{m}^3
\end{aligned}$$

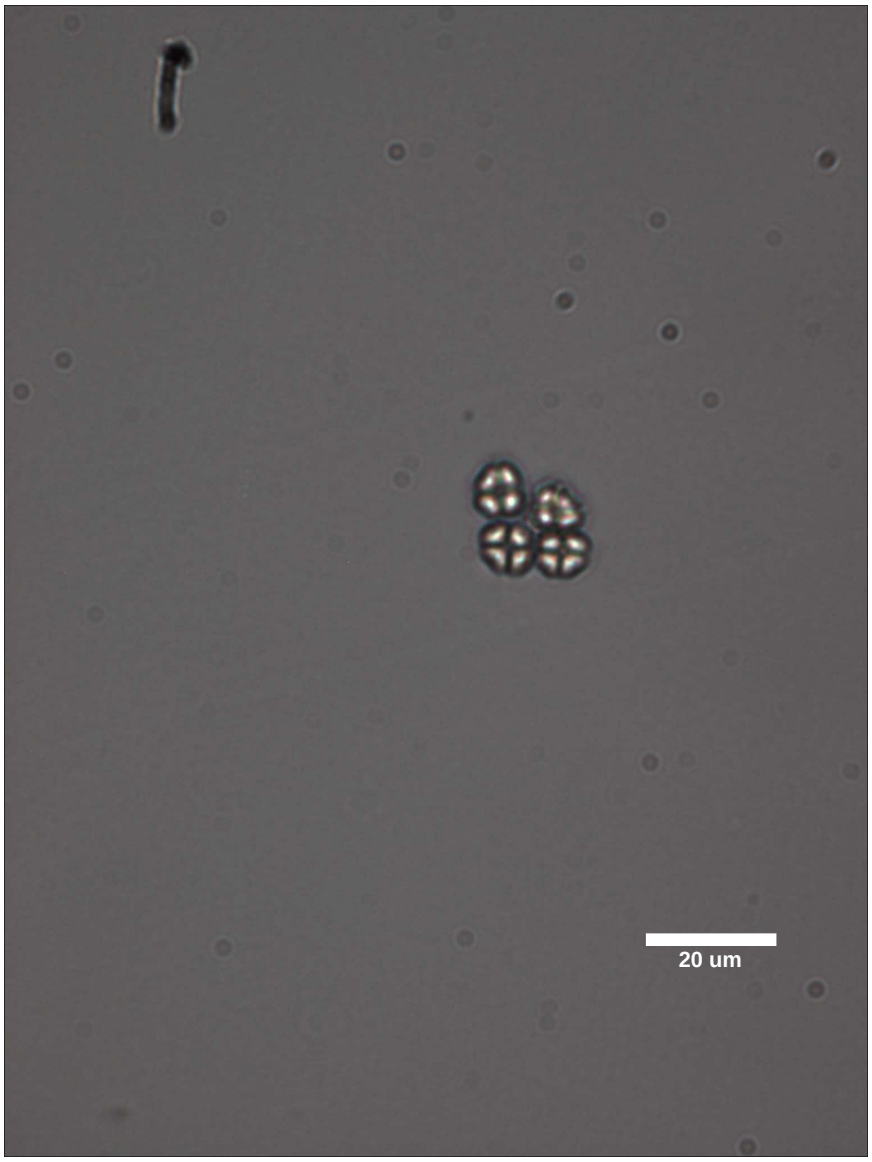


Figure 24: *Crucigenia* (green algae).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 2.51\,\mu\text{m} \\
\text{Avg. length} &= 2.11\,\mu\text{m} \\
\text{Avg. biovolume} &= 11.06\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 4.22 - 17.90\,\mu\text{m}^3
\end{aligned}$$

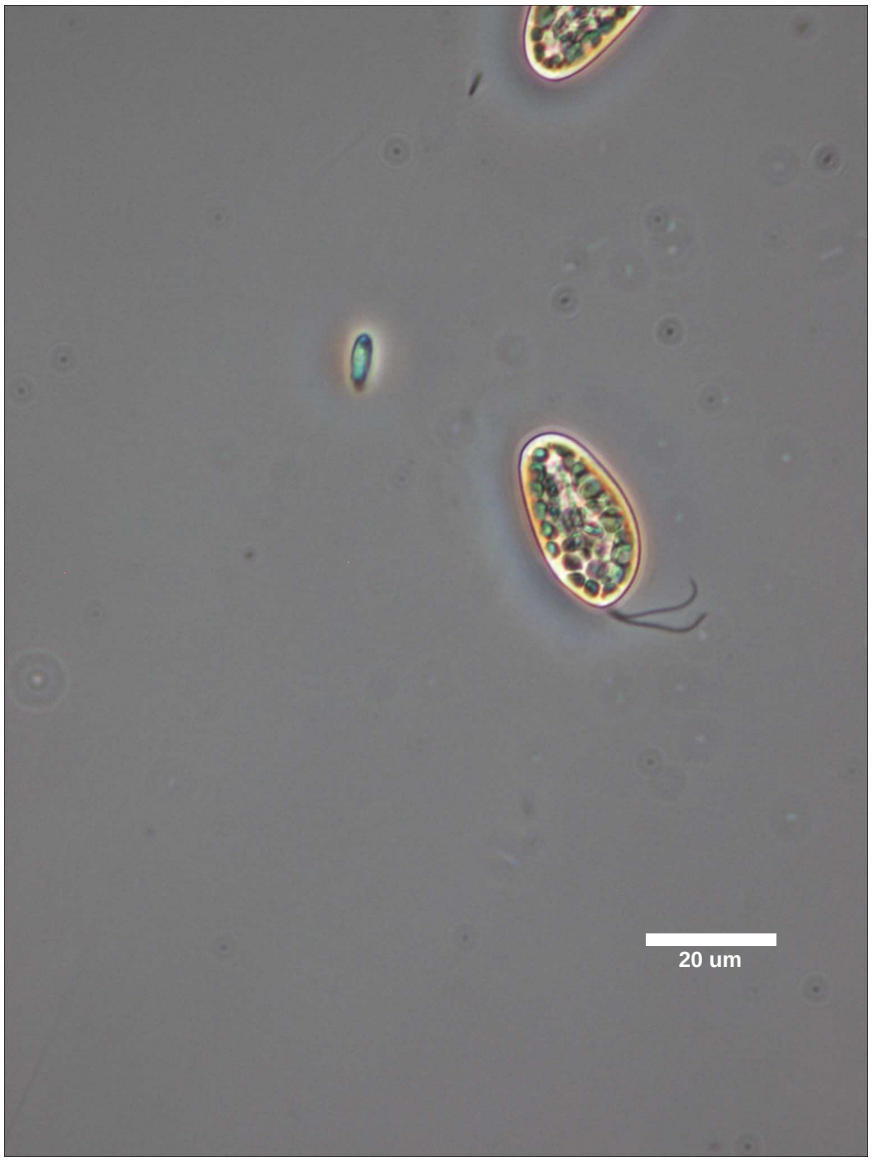


Figure 25: *Cryptomonas* (cryptomonad).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 8.85\,\mu\text{m} \\
\text{Avg. length} &= 17.51\,\mu\text{m} \\
\text{Avg. biovolume} &= 945.4\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 226.7 - 1,664\,\mu\text{m}^3
\end{aligned}$$

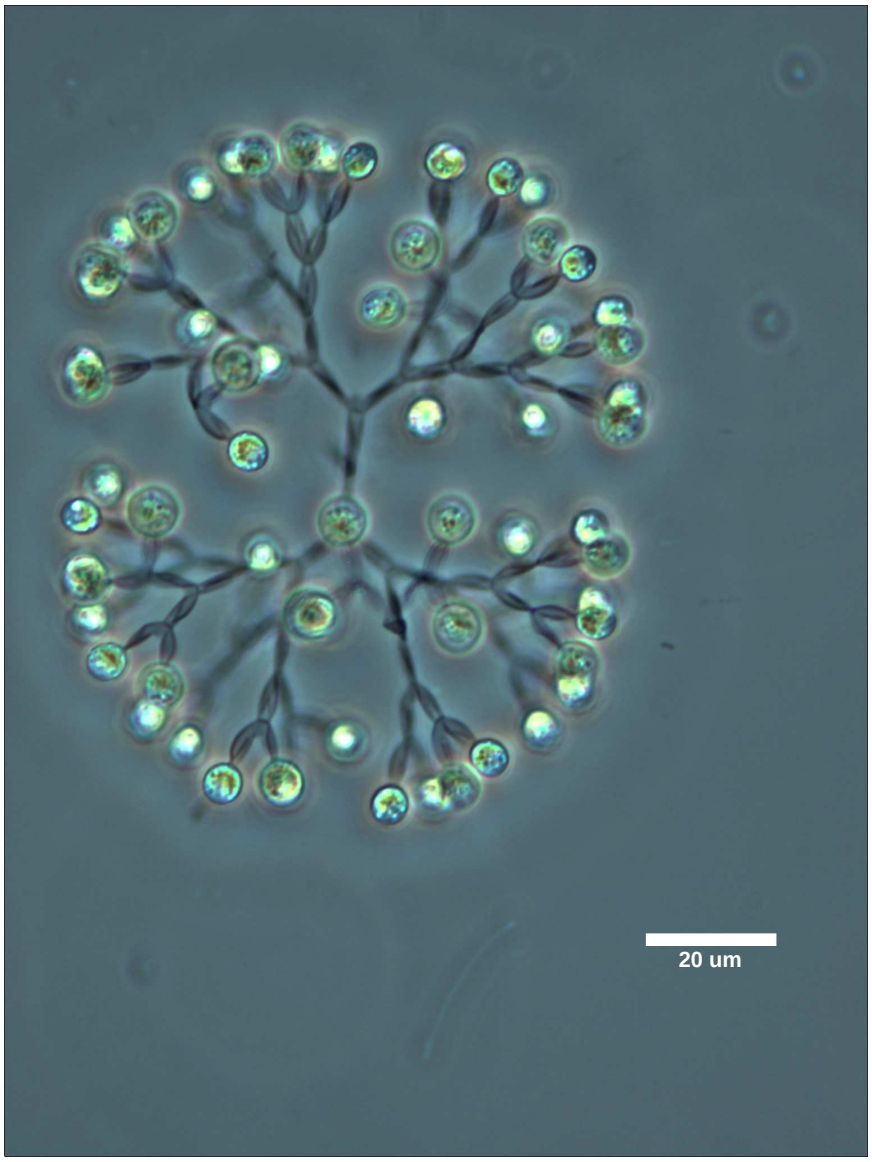


Figure 26: *Dictyosphaerium* (green algae).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 6.64\,\mu\text{m} \\
\text{Avg. length} &= 7.27\,\mu\text{m} \\
\text{Avg. biovolume} &= 169.2\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 138.2 - 200.2\,\mu\text{m}^3
\end{aligned}$$

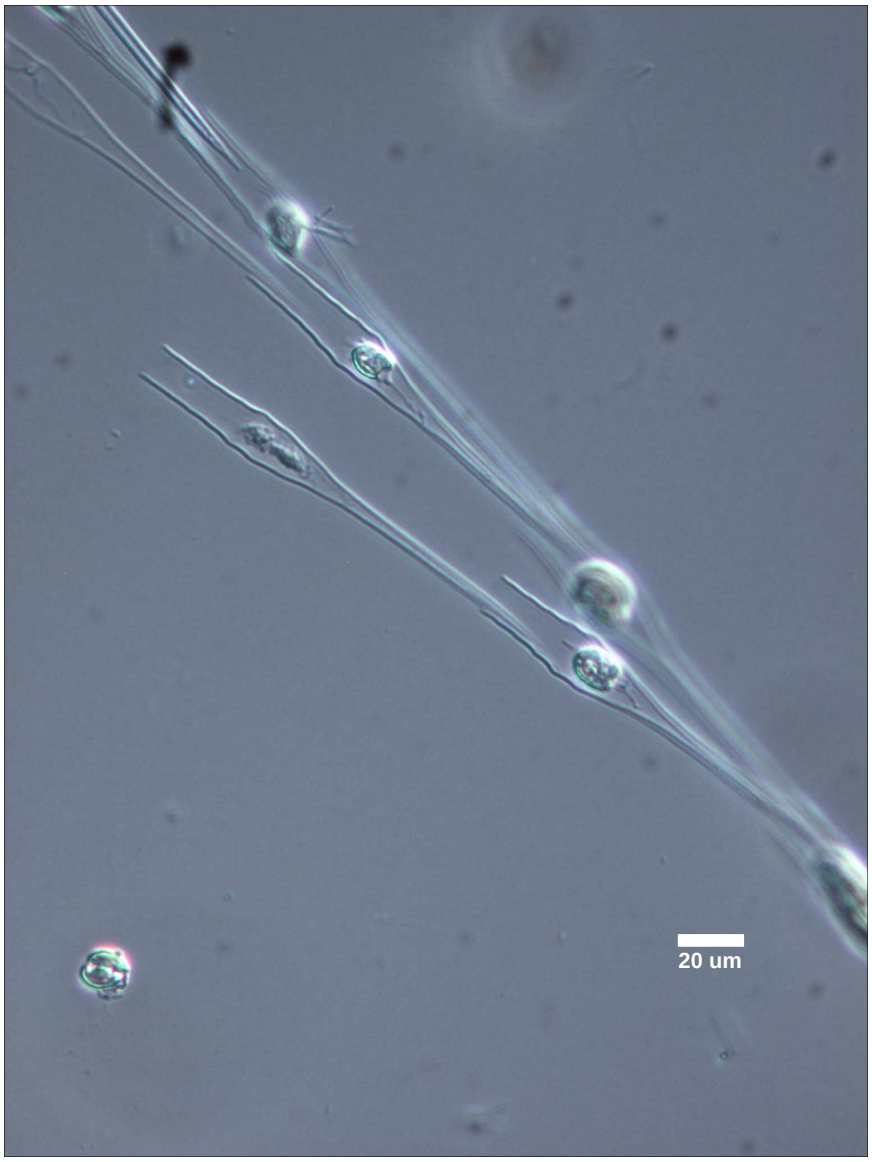


Figure 27: *Dinobryon bavaricum* (chrysophyte).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 2.51\,\mu\text{m} \\
\text{Avg. length} &= 8.06\,\mu\text{m} \\
\text{Avg. biovolume} &= 122.4\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 43.2 - 201.5\,\mu\text{m}^3
\end{aligned}$$

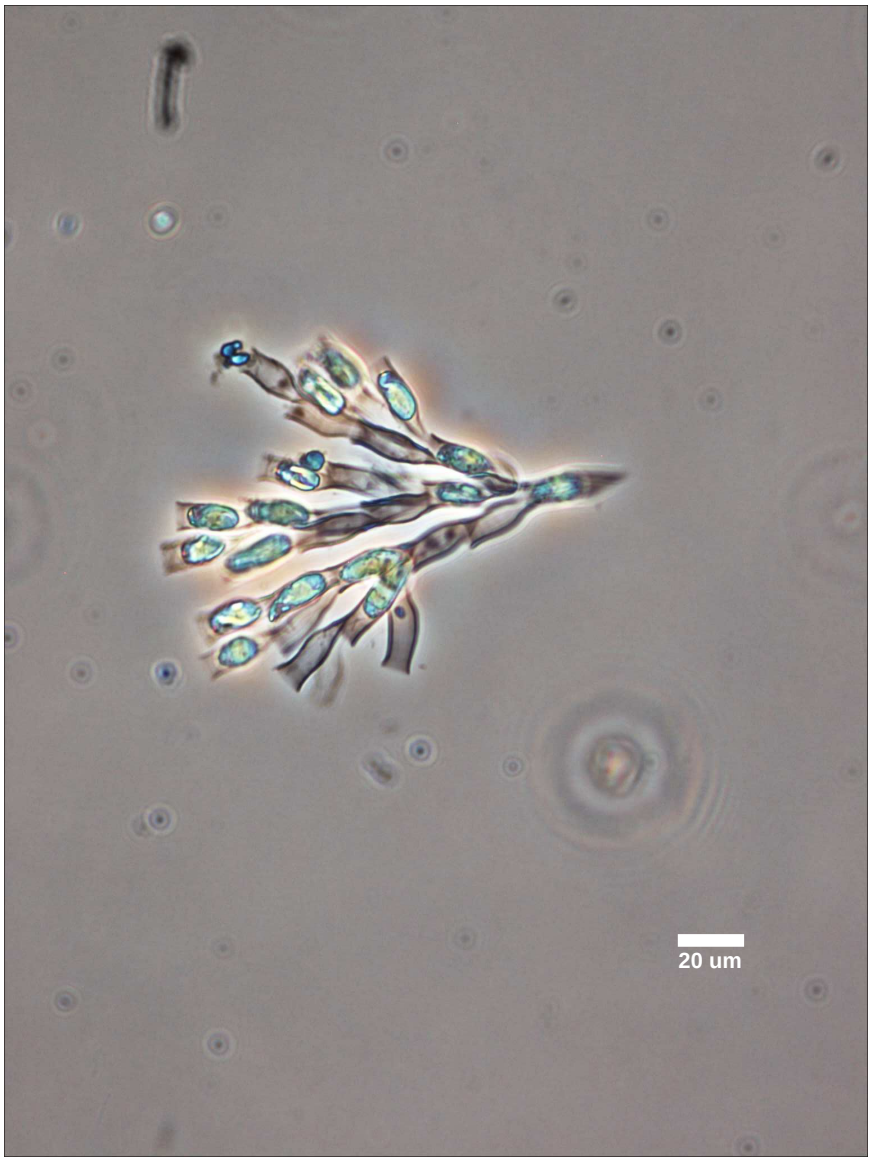


Figure 28: *Dinobryon sertularia* (chrysophyte).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 1.63\,\mu\text{m} \\
\text{Avg. length} &= 9.91\,\mu\text{m} \\
\text{Avg. biovolume} &= 17.2\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 6.81 - 27.6\,\mu\text{m}^3
\end{aligned}$$

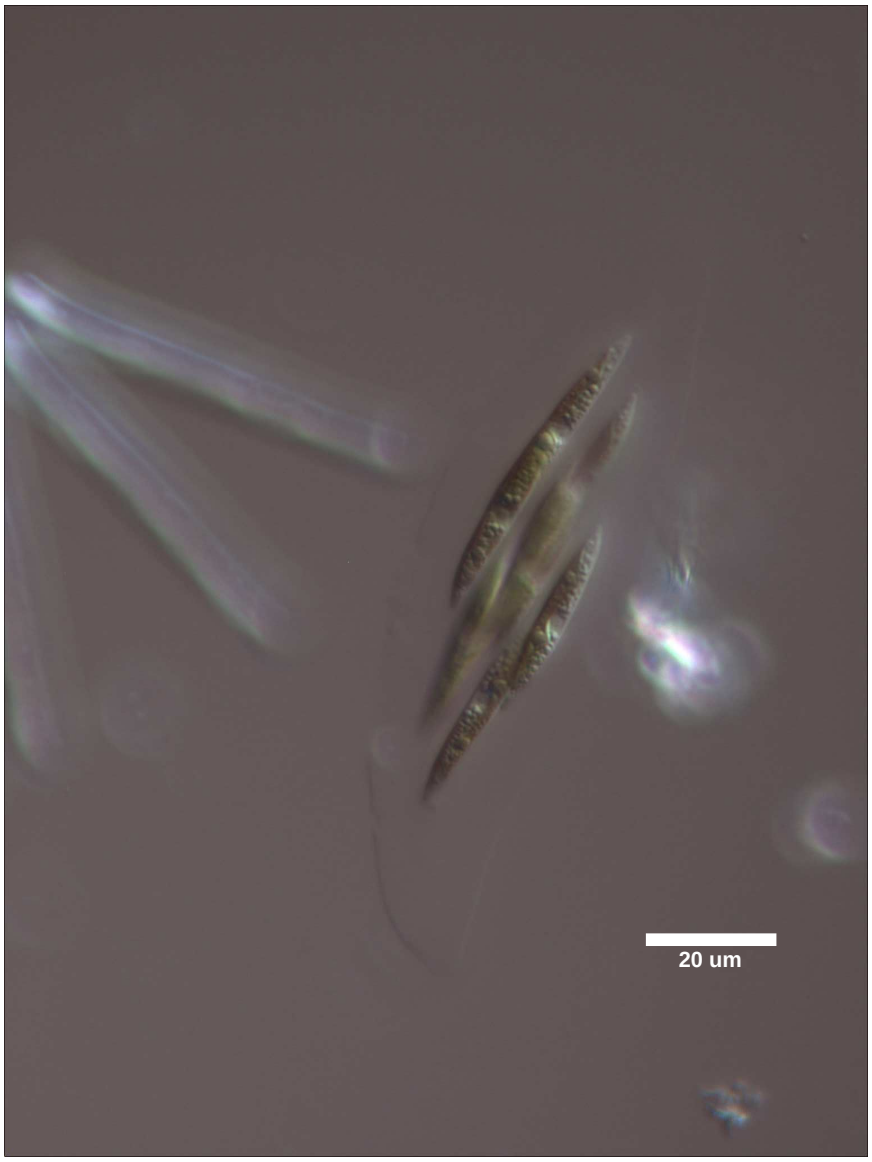


Figure 29: *Elakatothrix* (green algae).

$$\begin{aligned}
\text{Fusiform biovolume} &= \frac{2}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 1.64\,\mu\text{m} \\
\text{Avg. length} &= 14.58\,\mu\text{m} \\
\text{Avg. biovolume} &= 11.81\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 8.44 - 15.17\,\mu\text{m}^3
\end{aligned}$$

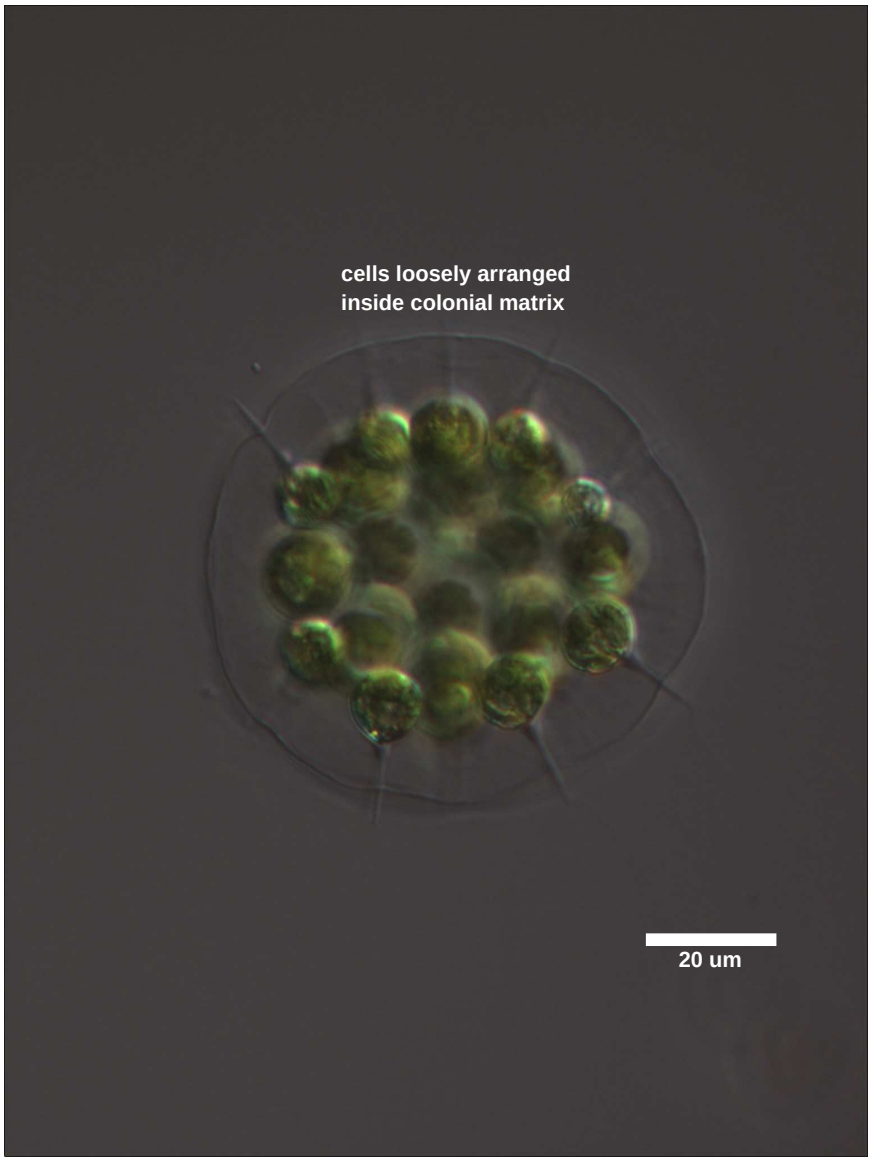


Figure 30: *Eudorina* (green algae).

$$\text{Ovoid biovolume} = \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right)$$

$$\begin{aligned}
\text{Avg. width} &= 5.41\,\mu\text{m} \\
\text{Avg. length} &= 5.99\,\mu\text{m} \\
\text{Avg. biovolume} &= 180.2\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 69.6 - 290.7\,\mu\text{m}^3
\end{aligned}$$

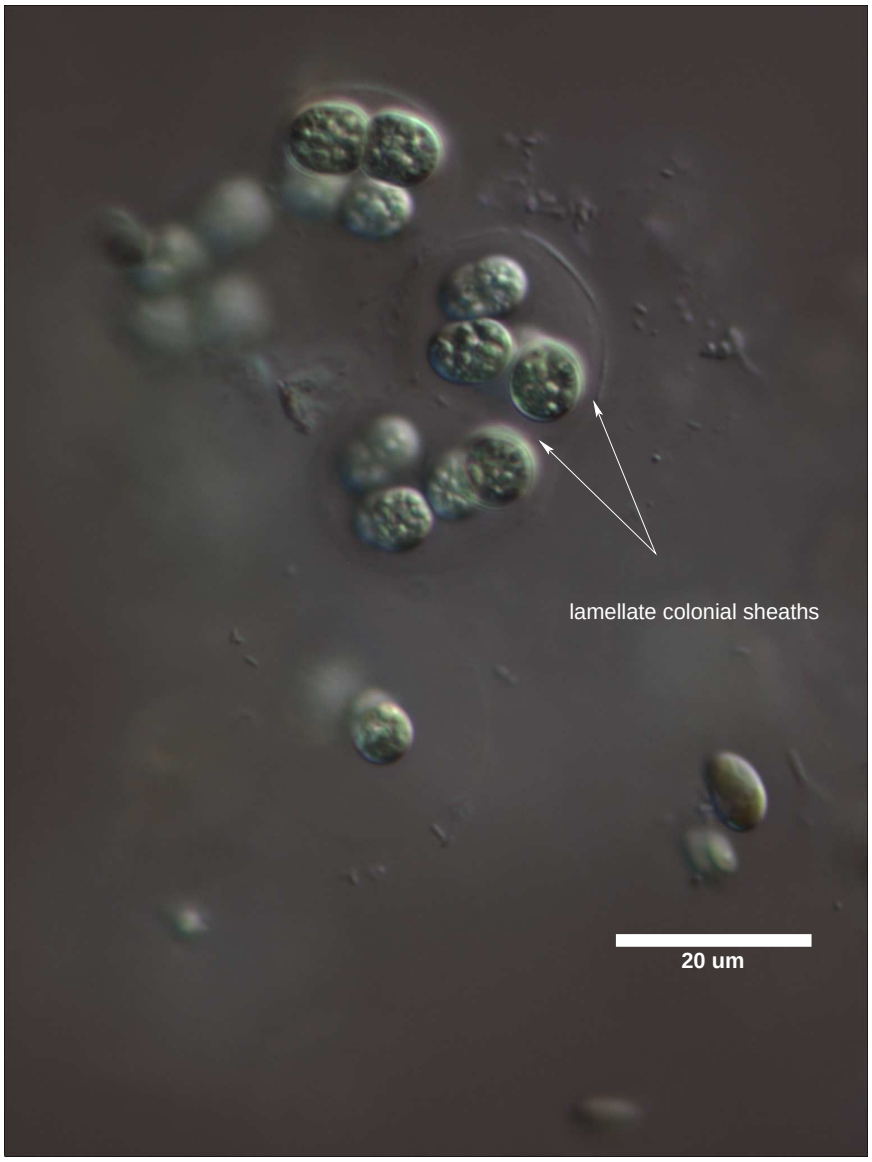


Figure 31: *Gloeocapsa* (cyanobacteria).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 6.0\,\mu\text{m} \\
\text{Avg. length} &= 6.5\,\mu\text{m} \\
\text{Avg. biovolume} &= 124.6\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 104.7 - 144.5\,\mu\text{m}^3
\end{aligned}$$

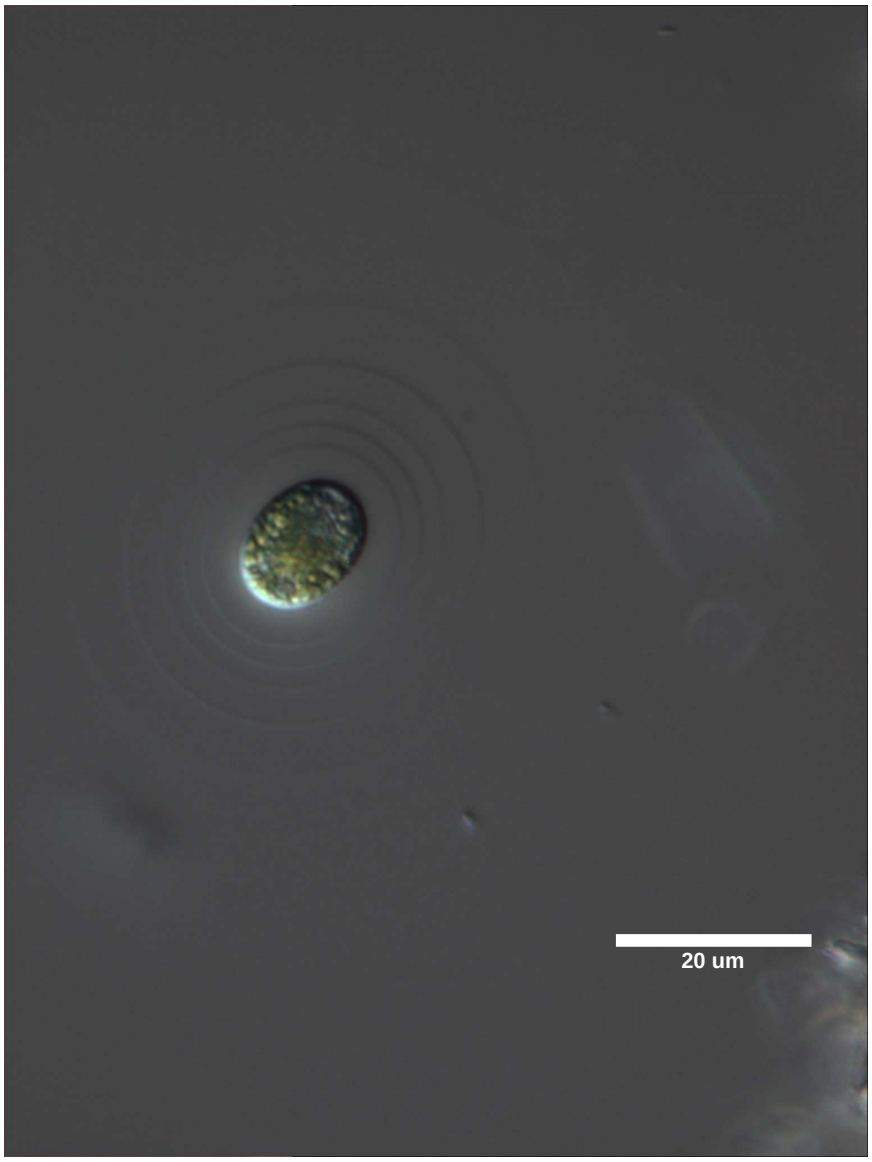


Figure 32: *Gloeocystis* (green algae).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 6.1\,\mu\text{m} \\
\text{Avg. length} &= 7.8\,\mu\text{m} \\
\text{Avg. biovolume} &= 153.1\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 120.8 - 185.5\,\mu\text{m}^3
\end{aligned}$$

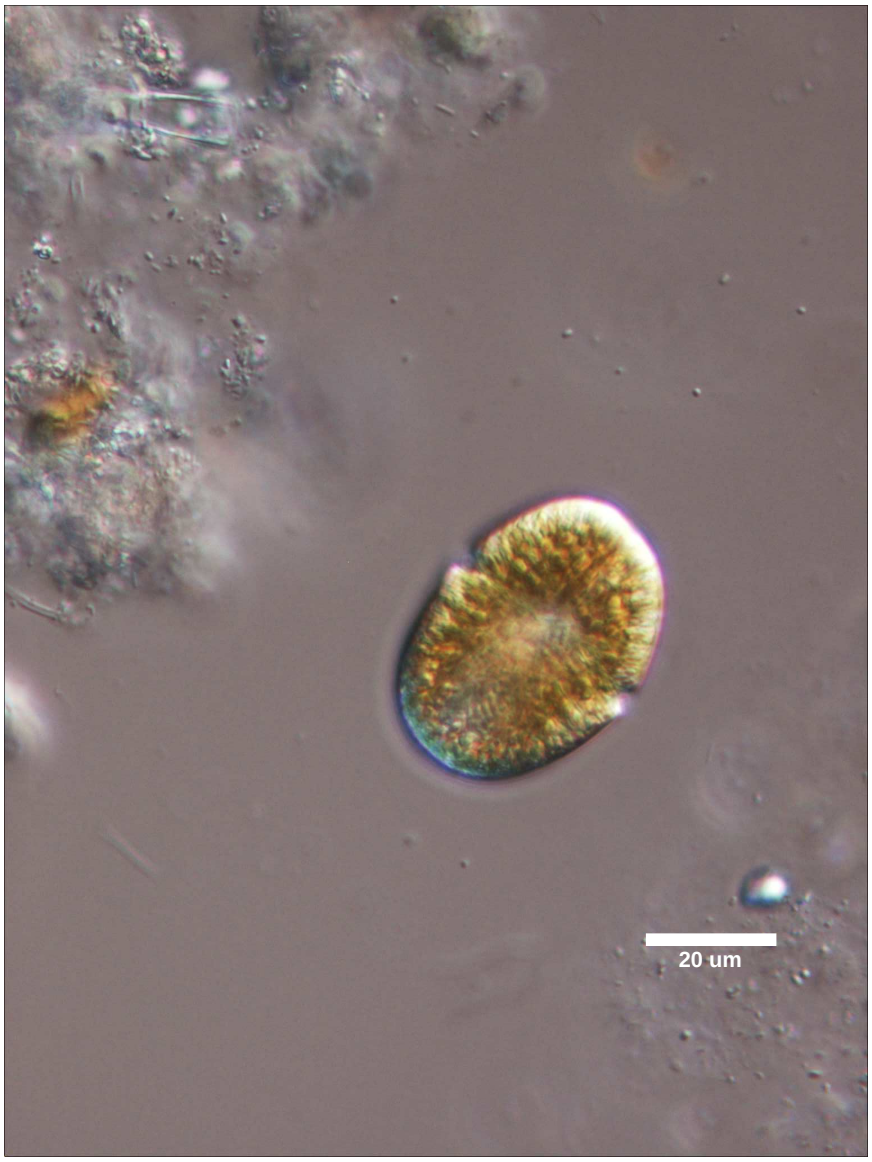


Figure 33: *Gymnodinium* (dinoflagellate).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 50.4\,\mu\text{m} \\
\text{Avg. length} &= 51.4\,\mu\text{m} \\
\text{Avg. biovolume} &= 70,953\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 53,043 - 88,863\,\mu\text{m}^3
\end{aligned}$$

Figure 34: *Komma caudata* (cryptomonad; a.k.a *Chroomonas acuta*)

$$\text{Ovoid biovolume} = \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right)$$

$$\begin{aligned}
\text{Avg. width} &= 3.84\,\mu\text{m} \\
\text{Avg. length} &= 7.18\,\mu\text{m} \\
\text{Avg. biovolume} &= 78.2\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= < 1 - 161.8\,\mu\text{m}^3
\end{aligned}$$

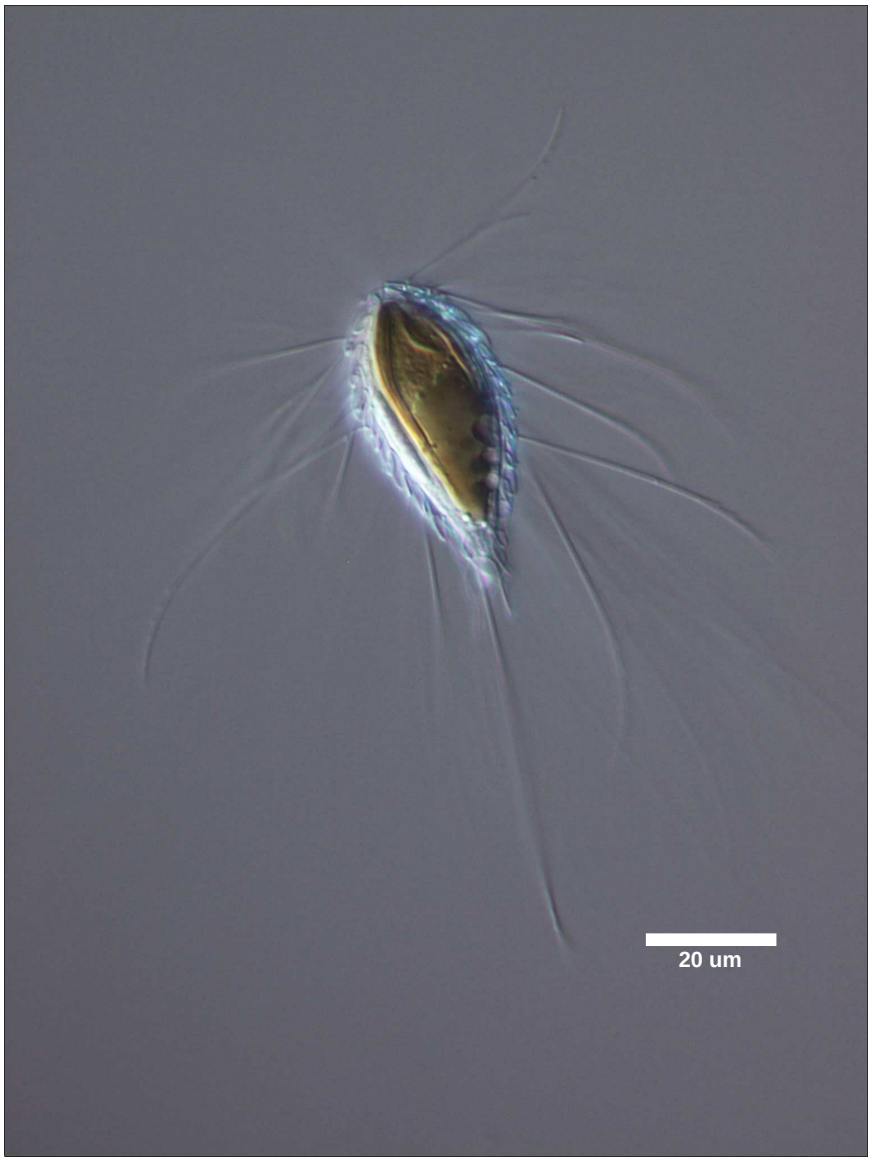


Figure 35: *Mallomonas* (chrysophyte).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 20.0\,\mu\text{m} \\
\text{Avg. length} &= 41.6\,\mu\text{m} \\
\text{Avg. biovolume} &= 8,951\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 6,989 - 10,913\,\mu\text{m}^3
\end{aligned}$$

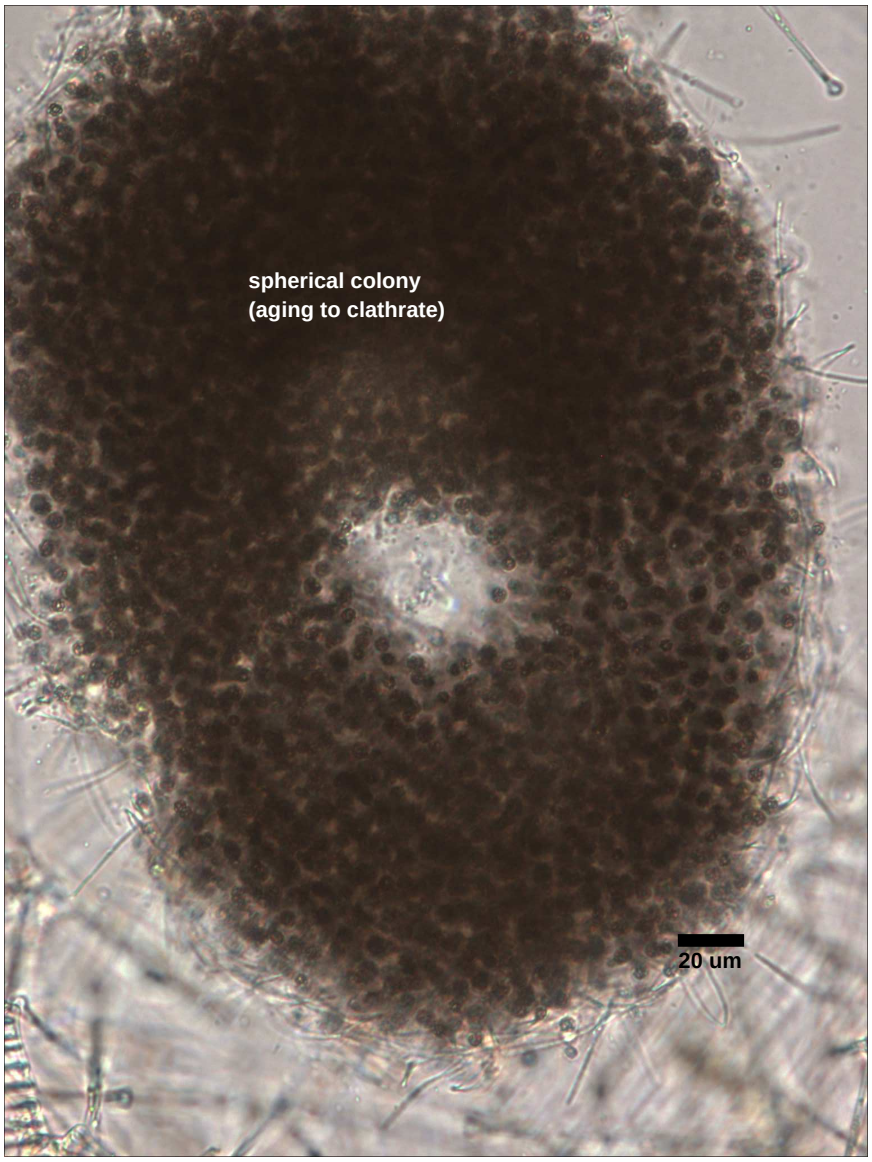


Figure 36: *Microcystis* (cyanobacteria).

$$\text{Ovoid biovolume} = \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right)$$

$$\begin{aligned}
\text{Avg. width} &= 5.42\,\mu\text{m} \\
\text{Avg. length} &= 6.17\,\mu\text{m} \\
\text{Avg. biovolume} &= 96.1\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 80.1 - 112.1\,\mu\text{m}^3
\end{aligned}$$

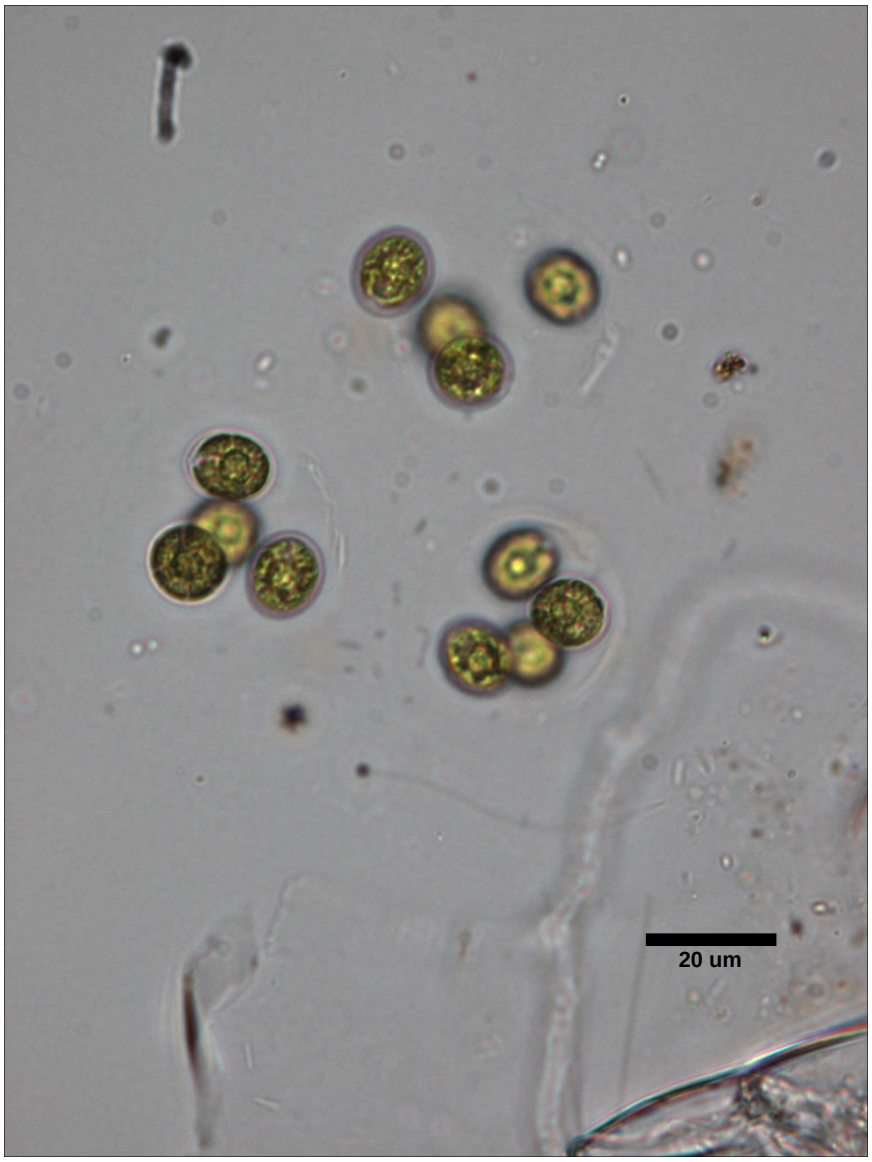


Figure 37: *Oocystis* (green algae).

$$\text{Ovoid biovolume} = \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right)$$

$$\begin{aligned}
\text{Avg. width} &= 5.48\,\mu\text{m} \\
\text{Avg. length} &= 8.38\,\mu\text{m} \\
\text{Avg. biovolume} &= 138.5\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 113.7 - 163.4\,\mu\text{m}^3
\end{aligned}$$

Figure 38: *Scenedesmus* (green algae).

$$\text{Ovoid biovolume} = \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right)$$

$$\begin{aligned}
\text{Avg. width} &= 2.89\,\mu\text{m} \\
\text{Avg. length} &= 9.20\,\mu\text{m} \\
\text{Avg. biovolume} &= 43.2\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 33.7 - 52.6\,\mu\text{m}^3
\end{aligned}$$

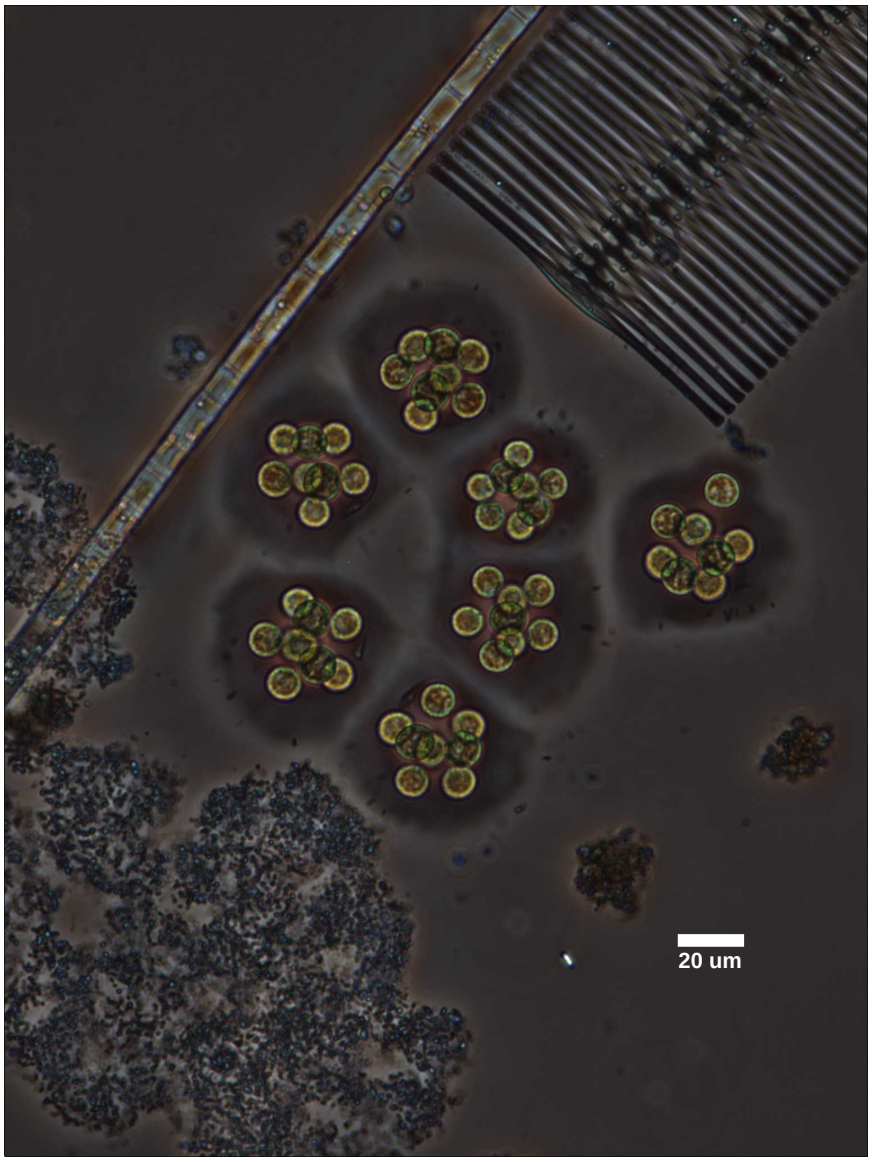


Figure 39: *Sphaerocystis* (green algae).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 1.53\,\mu\text{m} \\
\text{Avg. length} &= 1.64\,\mu\text{m} \\
\text{Avg. biovolume} &= 2.57\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 1.71 - 3.43\,\mu\text{m}^3
\end{aligned}$$

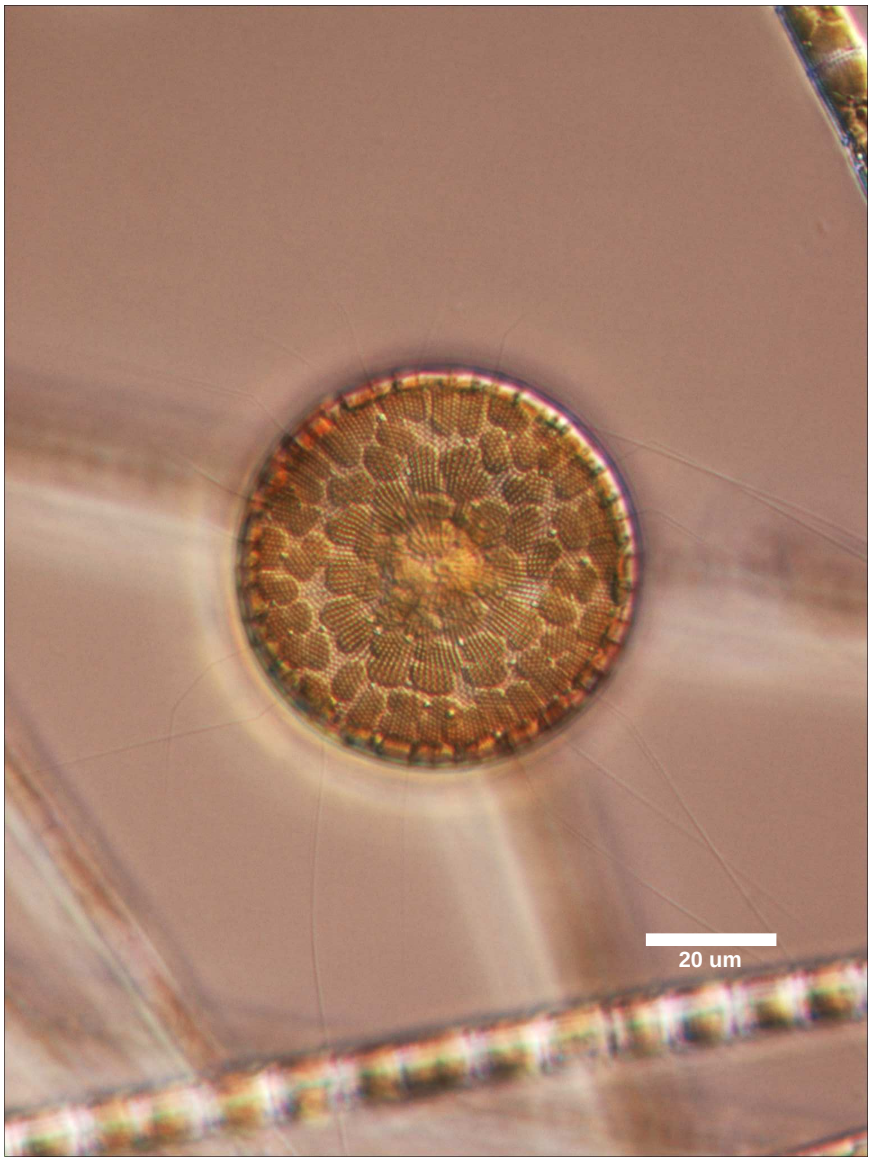


Figure 40: *Stephanodiscus* (chrysophyte - diatom).

$$\text{Cylinder biovolume} = \pi \left(\frac{\text{diameter}}{2} \right)^2 \times \text{depth}$$

$$\begin{aligned} \text{Avg. diameter} &= 48.8\,\mu\text{m} \\ \text{Avg. depth} &= 26.7\,\mu\text{m} \\ \text{Avg. biovolume} &= 51,354\,\mu\text{m}^3 \\ \text{Biovolume 95\% CI} &= 37,935 - 64,773\,\mu\text{m}^3 \end{aligned}$$

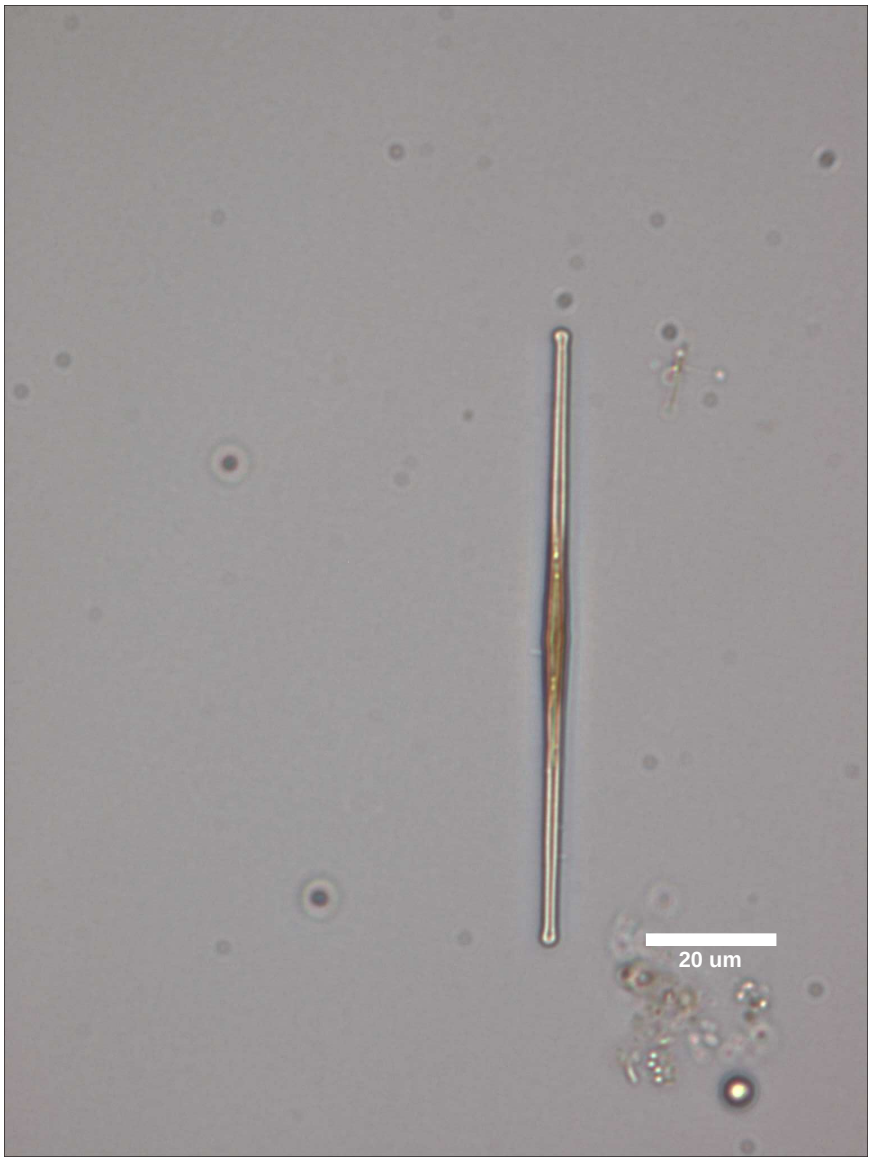


Figure 41: *Synedra* (chrysophyte - diatom).

$$\text{Diamondbox biovolume} = \text{width} \times \text{length} \times \frac{\text{depth}}{2}$$

$$\begin{aligned}
\text{Avg. width} &= 2.7\,\mu\text{m} \\
\text{Avg. length} &= 87.6\,\mu\text{m} \\
\text{Avg. depth} &= 1.7\,\mu\text{m} \\
\text{Avg. biovolume} &= 195.9\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 156.3 - 235.5\,\mu\text{m}^3
\end{aligned}$$

Figure 42: *Synura petersenii* (chrysophyte).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 7.8\,\mu\text{m} \\
\text{Avg. length} &= 12.8\,\mu\text{m} \\
\text{Avg. biovolume} &= 649.5\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= < 1 - 1,468\,\mu\text{m}^3
\end{aligned}$$

Figure 43: *Synura uvella* (chrysophyte).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 8.25\,\mu\text{m} \\
\text{Avg. length} &= 17.8\,\mu\text{m} \\
\text{Avg. biovolume} &= 653.1\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 481.9 - 824.2\,\mu\text{m}^3
\end{aligned}$$

Figure 44: *Tabellaria* (chrysophyte - diatom).

$$\begin{aligned}
\text{Rectangle biovolume} &= \text{length} \times \text{width} \times \text{depth} \\
\\
\text{Avg. width} &= 7.07\,\mu\text{m} \\
\text{Avg. length} &= 39.7\,\mu\text{m} \\
\text{Avg. depth} &= 2.38\,\mu\text{m} \\
\text{Avg. biovolume} &= 661.5\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 596.3 - 726.6\,\mu\text{m}^3
\end{aligned}$$

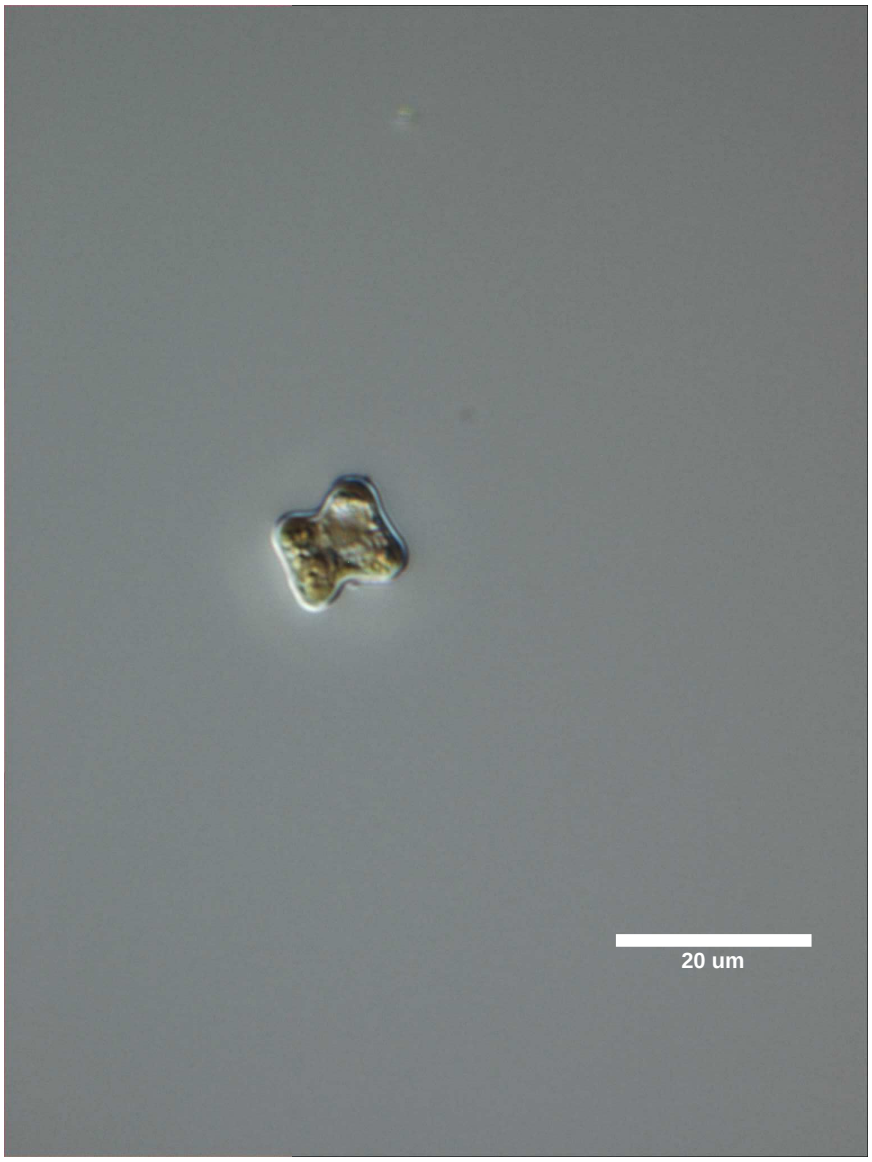


Figure 45: *Tetraedron* (green algae).

$$\begin{aligned}
\text{Box biovolume} &= \frac{(\text{length})^3}{4} \\
\\
\text{Avg. length} &= 19.8\,\mu\text{m} \\
\text{Avg. biovolume} &= 2,528\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 1,223 - 3,833\,\mu\text{m}^3
\end{aligned}$$

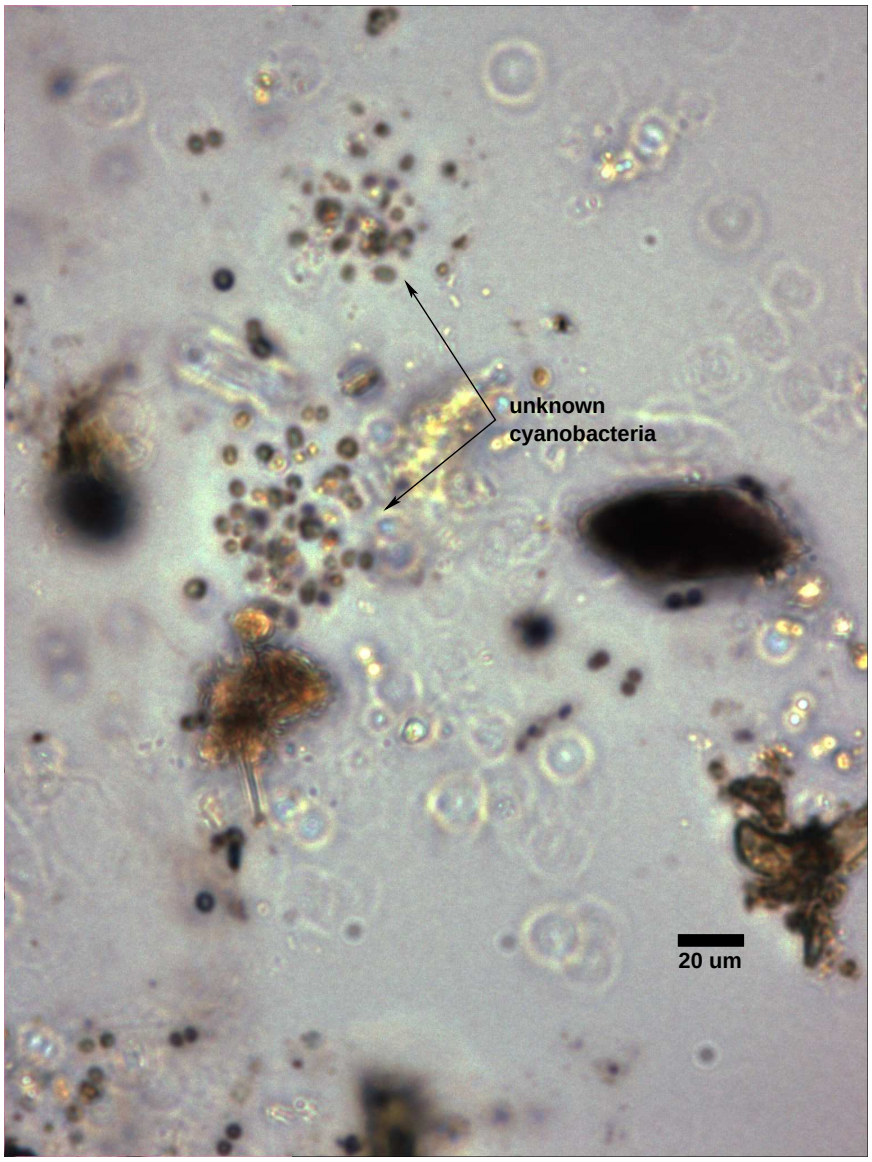


Figure 46: Unidentified bluegreen (cyanobacteria).

$$\text{Ovoid biovolume} = \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right)$$

$$\begin{aligned}
\text{Avg. width} &= 4.89\,\mu\text{m} \\
\text{Avg. length} &= 4.84\,\mu\text{m} \\
\text{Avg. biovolume} &= 63.7\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 46.0 - 81.4\,\mu\text{m}^3
\end{aligned}$$

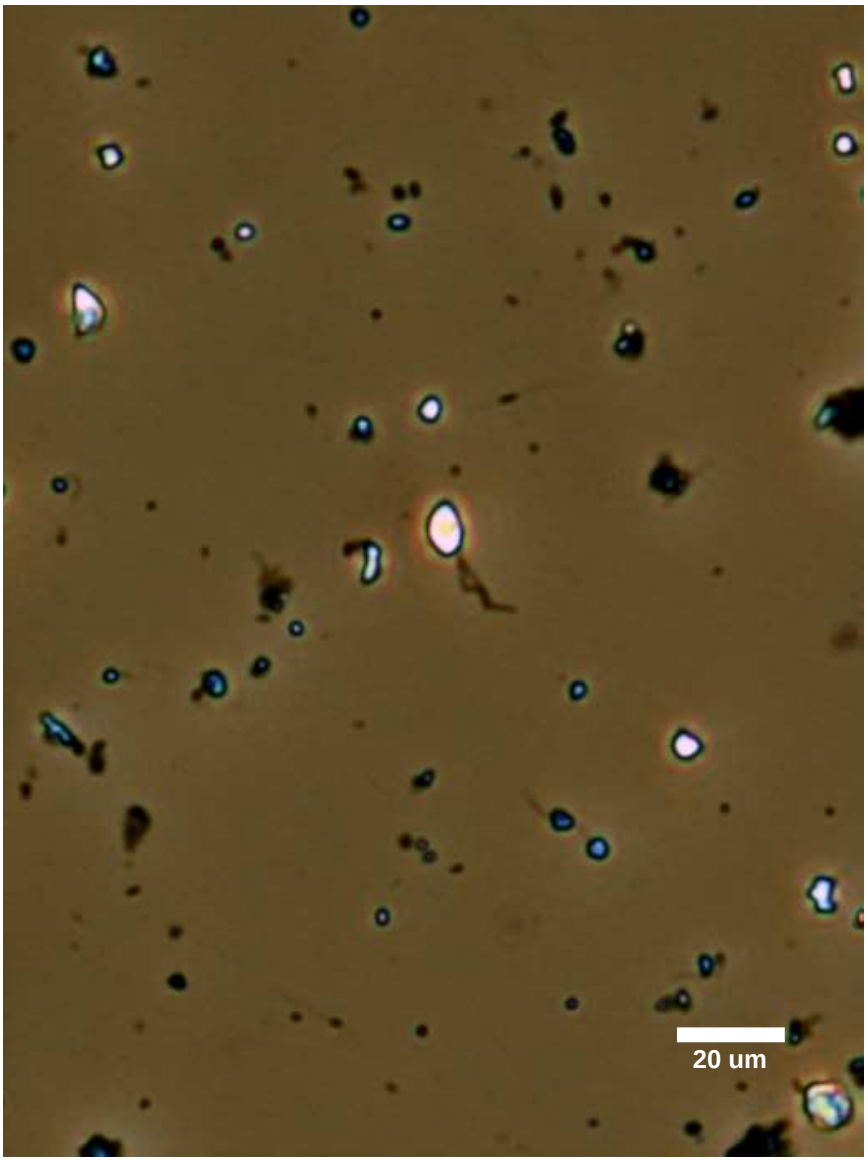


Figure 47: Unidentified golden (chrysophyte).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 2.5\,\mu\text{m} \\
\text{Avg. length} &= 4.3\,\mu\text{m} \\
\text{Avg. biovolume} &= 15.0\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 9.82 - 20.2\,\mu\text{m}^3
\end{aligned}$$

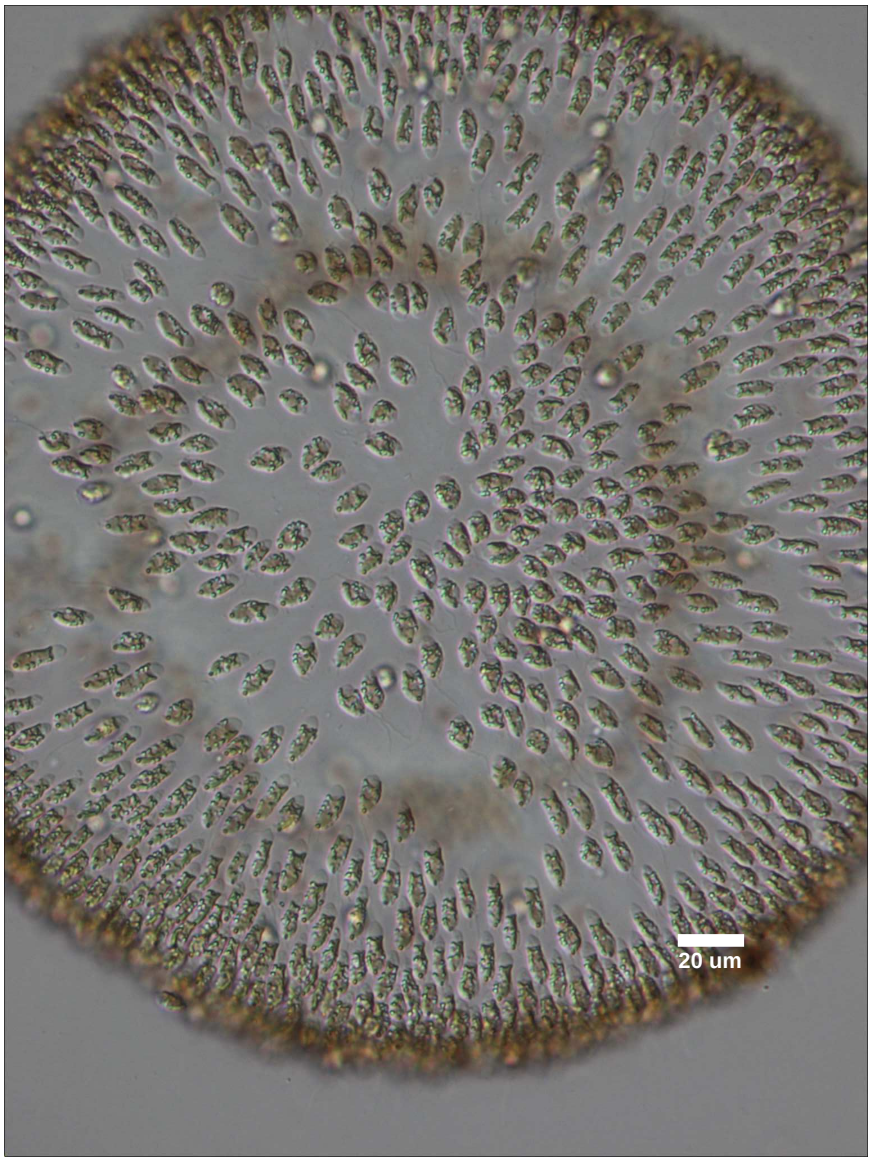


Figure 48: *Uroglena* (chrysophyte).

$$\begin{aligned}
\text{Ovoid biovolume} &= \frac{4}{3}\pi \times \left(\frac{\text{width}}{2}\right)^2 \times \left(\frac{\text{length}}{2}\right) \\
\text{Avg. width} &= 6.50\,\mu\text{m} \\
\text{Avg. length} &= 7.11\,\mu\text{m} \\
\text{Avg. biovolume} &= 165.0\,\mu\text{m}^3 \\
\text{Biovolume 95\% CI} &= 130.9 - 199.1\,\mu\text{m}^3
\end{aligned}$$

B Judy Reservoir Water Quality and Algae Data

Printed versions of this report include tables of the 2006–2009 data, edited to show detection limits. Online reports do not include copies of the original data, but electronic data files are available from the Institute for Watershed Studies. In addition, the IWS web site (http://www.ac.wwu.edu∼iws) features "dynamic" plots of the water quality data and tables containing the most recent results from the lake.

These pages represent updated water quality data, algal counts, and algal biovolume estimates, and should serve as the verified data source for results collected from October 2006 through October 2008. Electronic copies of the verified data are available from the Institute for Watershed Studies (IWS), Western Washington University, Bellingham, WA.

The code "NA" has been entered into all empty cells in the ascii data files to fill in unsampled dates and depths, missing data, etc. Questions about specific missing data should be directed to the IWS director.

Unless otherwise indicated, the electronic data files have NOT been censored to flag or otherwise identify below detection and above detection values. As a result, the ascii files may contain negative values due to linear extrapolation of the standards regression curve for below detection data. It is essential that any statistical or analytical results that are generated using these data be reviewed by someone familiar with statistical uncertainty associated with uncensored data.