Calculation of Phytoplankton Cell Biomass Estimates for the Chesapeake Bay Program

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In recent years, there has been an increased recognition of the value of phytoplankton cell biovolumes calculated from size and shape estimates, and the cellular carbon content derived from those biovolumes. Taxon-specific biovolumes and carbon estimates are providing new insights into the structure and function of phytoplankton communities in estuarine systems. There are a number of laboratories in the Chesapeake Bay region that routinely enumerate estuarine phytoplankton. The laboratories have been compiling cell dimensions for the Bay's phytoplankton taxa from taxonomic keys and actual microscope cell measurements for many years. In 2007, there was a coordinated effort between the phytoplankton laboratories at Old Dominion University in Virginia and the Morgan State University Patuxent Environmental & Aquatic Research Laboratory (previously the Academy of Natural Sciences Estuarine Research Center in Maryland) to compile a unified comprehensive master list of cell dimensions, biovolumes and carbon factors for Chesapeake Bay. These laboratories were responsible for the Virginia and Maryland phytoplankton monitoring programs, respectively, of the Chesapeake Bay Program (CBP) since 1984. Approximately 1400 unique phytoplankton taxa are identified in the CBP monitoring data record (J. Johnson, personal comm.).

The master taxa list has taxon-specific cell dimensions, codes for the geometric shapes that most closely resemble the taxon shape, the equations used to calculate cell biovolumes, and cell biovolume and carbon estimates for each taxon. It has become common practice to estimate cell biovolumes using geometric shapes, and there are literature sources which identify geometric shape assignments for numerous taxa (Kovala and Larrance, 1966; Edler 1979; Hillebrand et al., 1999, Sun and Liu 2003, Olenina et al., 2006; Vadrucci et al., 2007). With some noted exceptions, geometric shapes were assigned to individual taxa as recommended in Hillebrand (1999). Cell dimensions derived from actual microscope cell measurements were preferred to dimensions derived from taxonomic keys, and the later was used when no cell measurements were available.

There are two schools of thought in the phytoplankton biovolume literature about the assignment of geometric forms for the calculation of biovolume. Some have recommended the use of complex geometric forms to approximate the actual configuration of plankton cells for the calculation of biovolume (Kovala and Larrance, 1966; Hillebrand et al., 1999; Sun and Liu, 2003). However, complex geometric shapes such at the cymbelloid and gomphonemoid proposed by Hillebrand et al. (1999) or composites of multiple shapes (example-elliptical prism plus four cones) as suggested in Sun and Liu (2003) require detail measurement of complex angles and projection from the cell body that are difficult to make. Other sources advocate the use of simpler geometric forms contending less bias (Edler 1979; Vadrucci 2007) although simpler shapes tend to over estimated biovolume.

The detailed measurements required to calculate biovolume from complex shapes were not available in the laboratory measurements of cell dimensions; therefore, we opted to use the simplest geometric shape possible. It was a community consensus that even a slight overestimation of biovolume was acceptable because taxa cell sizes vary greatly in estuarine systems due to environmental conditions. Currently there are twenty-one shapes employed in the Chesapeake Bay master list (Table 1). Dimensions have been compiled for 986 taxa found in the CBP phytoplankton monitoring record. Source(s) of the dimensions are listed in Table 2.

There are four notable simplifications to shape codes recommended by Hillebrand et al. (1999). The cymbelloid shapes recommended by Hillebrand et al. for the genera *Amphora*, *Auricula*, *Cymbella*, *Encyonema*, *Hemidiscus*, and *Rhopalodia* were simplified to ellipsoids. Shapes for the genera

Actinastrum and *Ankistrodesmus* were simplified to prolated spheres from cylinder+ 2 cones. Species in the genera *Chataeteroceros* were estimated as cylinders, where the recommended shape is an elliptical prism. Taxa in the genus *Chattonella* were estimated using a shape of a cone plus half sphere.

The conversion of cell biovolume to carbon was based on protocols and equations described by Smayda (1978). The following equation was used for all phytoplankton other than diatoms:

Equation 1 $\log_{10}C = (0.866 * \log_{10}(TV)) - 0.46$

Where TV is the total cell biovolume in cubic microns (μm^3) and C is the estimated cell carbon content in picograms per cell (pg/cell). C equals the antilog of $\log_{10}C$, or 10 raised to the power of $\log_{10}C$.

For all diatoms, it is necessary to subtract the volume of the cell vacuole from the cytoplasm volume and then calculate carbon content. First, the thickness of the cell cytoplasm layer is estimated from the ratio of total cell surface area (TA) in μm^2 to total cell volume (TV):

Ratio of Total Cell Area (TA) to Total Cell Volume (TV)	Cytoplasmic Layer Thickness
X < 0.35	2 µm
0.35 $\leq$ X > 0.50	1.5 µm
0.50 - 0.89	1 µm
$\geq$ 0.90	*

*Plasma volume equals the total volume.

Cell plasma volume (PV) in μm^3 is then calculated using an equation from Smayda (1978):

Equation 2 $PV = ((TA \text{ in } \mu m^2) * (\text{Cytoplasmic Layer Thickness})) + (0.1 * TV \text{ in } \mu m^3)$

Finally, the following equations are used to convert plasma volume to a carbon estimate. For diatoms where the TA:TV ratio is < 0.9:

Equation 3 $\log_{10}C = 0.892 \log_{10}(PV) - 0.61$

Equation 4 $\log_{10}C = 0.758 \log_{10}(TV) – 0422$

Approximately 405 taxa found in Chesapeake Bay did not have measured dimensions or had carbon estimates without documented dimensions. For 71 of these taxa, biovolumes and surface areas were derived by computing a mean of all carbon values for all taxa in the genus, family, or group (method codes FAMILY_AVE, GENUS_AVE, or GROUP_AVE in Table 2). For the remaining 334 taxa, the provided carbon value was accepted as the best available and a biovolume was back calculated using the appropriate equations from Smayda (1978). In all cases where diatom biovolumes were back calculated, the plasma volume was assumed to equal the total cell volume (method codes CBP_EST_T1 and CBP_EST_TB in Table 2).

When biovolume was back calculated, it was sometimes possible to use the cell shape to derive estimates of the cell dimensions. Any cell where the assigned shape was a sphere or a cube requires only one measured dimension to calculate a biovolume. The back calculated dimensions were spot checked against dimensions reported in taxonomic keys to assess whether derived values were realistic values. There were 96 taxa where both biovolume and dimensions were back calculated (method code: CBP_EST_TB).

An additional 352 taxa had carbon values provided but the taxa is not currently found in the CBP monitoring record (method CBP_EST_T2). These data had their biovolume calculated as described.

Citations:

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Table 1 Geometric Equations for the Estimation of Cell Volumes and Surface Areas

CODE	SHAPE	VOLUME	SURFACE AREA
1	SPHERE	$\frac{\pi}{6} * D^3$	$\pi * D^2$
2	CYLINDAR	$\frac{\pi}{4} * D^{2*} H$	$\pi * D * \left(\frac{D}{2} + H\right)$
3	ELLIPSEOID	$\frac{\pi}{6} * D * H * W$	$\frac{\pi}{4} * (D+W) * \left[\left(\frac{D+W}{2}\right) + \frac{2H^2}{\sqrt{4 * H^2 - (D+W)^2}} SIN^{-1} \frac{\sqrt{4H^2 - (D+W)^2}}{2D}\right]$
4	CONE	$\frac{\pi}{12} * D^2 * H$	$\frac{\pi}{2} * D * \left(\frac{D}{2} + \sqrt{\left(H^2\right) + \left(\frac{D}{2}\right)^2}\right)$
5	TRAPEZOIDAL PRISM	$\frac{1}{2} * H * DE * (W + W2)$	SHAPE NOT IN CURRENT USE
6	CUBE	W^3	$6 * W^2$
7	RETANGULAR BOX	$H * W * DE$	$(2 * H * W) + (2 * W * DE) + (2 * H * DE)$
8	TRUNCATED CONE	$\frac{\pi}{12} * H * \left(D^2 + (D * D2) + D2^2\right)$	$\frac{\pi}{4} * \left(D2^2 + D^2 + 2h(D2 + D)\right)$
9	TRIANGULAR PRISM	$\frac{1}{2} * H * W * D$	$(W * DE) + (3 * H * W)$

CODE	SHAPE	VOLUME	SURFACE AREA
10	ELLIPTICAL PRISM	$\frac{\pi}{4} * H * W * DE$	$\frac{\pi}{2}\left(H * W + \left(H + W\right) * DE\right)$
11	CONE+HALF SPHERE	$\frac{\pi}{12} * D^2 * \left(H + D\right)$	$\frac{1}{2} * \pi * D * \left(L + D\right)$
12	NOT ASSIGNED		
13	NOT ASSIGNED		
14	DUMBELL	$2 * \left(\frac{\pi}{6} * D^3 \right)$	$2 * \pi * D^2$
15	PRISM ON PARALLELOGRAM	$\frac{\pi}{2} * H * W * DE$	$W * H + \left(\frac{\sqrt{H^2 + W^2}}{4}\right) * DE$
16	PYRAMID	$\frac{1}{3} H * W * DE$	SHAPE NOT IN CURRENT USE
17	CYLINDER+ 2 HALF SPHERES	$\pi * D^2 * \left(\frac{H}{4} + \frac{D}{6}\right)$	$\pi * D * \left(D + H\right)$
18	PROLATE SPHERE	$\frac{\pi}{6} * D^2 * H$	$\frac{\pi * D}{2} * \left(D + \frac{H^2}{\sqrt{H^2 - D^2}} * SIN^{-1}\left(\frac{\sqrt{H^2 - D^2}}{H}\right)\right)$

CODE	SHAPE	VOLUME	SURFACE AREA
19	2 CONES	$\frac{\pi}{12} * D^2 * H$	$\pi * D * \sqrt{H^2 + \left(\frac{D}{2}\right)^2}$
20	HALF SPHERE	$\frac{\pi}{12} * D^3$	$\frac{3\pi}{4} * D^2$
21	CYLINDER + CONE	$\left(\frac{\pi}{4} * D^2 * H\right) + \left(\frac{\pi}{12} * D^2 * H2\right)$	$\left(\pi * \left(\frac{D}{2}\right)^2\right) + \left(2 * \pi * \frac{D}{2} * H\right) + \left(\pi * \frac{D}{2} * \left(H^2 + \left(\frac{D}{2}\right)^2\right)\right)$
22	CYMBELLOID	USE ELLIPESOID EQUATIONS	USE ELLIPESOID EQUATIONS
23	2 ELLIPSEOID	$\frac{\pi}{6} * D * H * W * 2$	$\frac{\pi}{4} * (D+W) * \left[\left(\frac{D+W}{2}\right) + \frac{2H^2}{\sqrt{4 * H^2 - (D+W)^2}} SIN^{-1} \frac{\sqrt{4H^2 - (D+W)^2}}{2D}\right] * 2$
24	SICKLE SHAPED PRISM	$\frac{\pi}{4} * H * DE * W$	$\frac{\pi}{4} * (H * W + DE * W + H * DE) + H * DE$

TABLE 2: Method codes

Estimate _Method	Description
AVE_GEN_DIM	Dimensions provided were calculated as average for all taxa in genus - 2008
BALTIC_LIST	Dimensions provided Checklist of Baltic Sea Phytoplankton Species
CBP_EST_2008_T1	Taxa found in CBP monitoring data, ODU provided carbon value without dimensions, biovolume back calculated from carbon value
CBP_EST_2008_T2	Taxa not found in CBP monitoring data, ODU provided carbon value without dimensions, biovolume back calculated from carbon value
CBP_EST_2008_T3	Taxa not found in CBP monitoring data, no carbon value provided
CBP_EST_2008_TB	Taxa found in Chesapeake Bay and carbon value provided by ODU without dimensions. Shapes were either sphere or square and biovolumes and dimensions were back calculated from carbon value.
FAMILY_AVE	Biovolume and surface area are the average for all taxa in family - 2008
GENUS_AVE	Biovolume and surface area are the average for all taxa in genus - 2008
GROUP_AVE	Biovolume and surface area are the average for all taxa in group - 2008
JJ_2008	Dimensions provided by Jackie Johnson from taxon keys - 2008
MSU_2007	Dimensions provided by Richard Lacouture from taxon keys & lab measurements - 2007
MSU_2006	Dimensions provided by Richard Lacouture from taxon keys & lab measurements - 2006
MSU_FEB_08	Dimensions provided by Richard Lacouture from taxon keys & lab measurements - 2008
MSU_APR_01	Dimensions provided by Richard Lacouture from taxon keys & lab measurements - April 2001
MSU_SEP_01	Dimensions provided by Richard Lacouture from taxon keys lab & measurements - Sept 2001
ODU_2008	Dimensions provided by Todd Egerton ODU - 2008
ODU_2006	Dimensions provided by Todd Egerton ODU - 2006
SELLNER_2008	Dimensions provided by Kevin Sellner from taxon keys - Feb 2008
SERC_2007	Dimensions provided by Sharyn Hedrick from taxon keys & lab measurements - Fall 2007
SERC_FEB_08	Dimensions provided by Sharyn Hedrick from taxon keys - Feb 2008