Comparisons of Measured Productivity and the Composite Parameter BZ_pI_0 in Massachusetts Bay 2001-2010

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COMPARISONS OF MEASURED PRODUCTIVITY AND THE COMPOSITE PARAMETER BZ_PI_0 IN MASSACHUSETTS BAY 2001-2010

Prepared by

Kenneth E. Keay[1]
David I. Taylor[1]
Maurice P. Hall[1]
Wendy S. Leo[1]
and
P. Scott Libby[2]

[1]MASSACHUSETTS WATER RESOURCES AUTHORITY
Environmental Quality Department and
Department of Laboratory Services
100 First Avenue
Charlestown Navy Yard
Boston, MA 02129
(617) 242-6000

[2]Battelle
397 Washington Street,
Duxbury, MA 02332

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1.0 Introduction

Revisions to MWRA's Ambient Monitoring Plan for the MWRA Effluent Outfall (MWRA 2010) were approved by regulators and became effective in December 2010; the changes included ending laboratory measurements of primary productivity, which is the rate of growth of marine plants in the presence of sunlight and nutrients. However, the Ambient Monitoring Plan Revision 2 does require MWRA to produce two reports on estimates of primary production. The first report (Keay et al. 2012) summarizes comparisons made between field measurements of primary productivity and those modeled using MWRA's water quality model, the Bays Eutrophication Model (BEM). This report fulfills the second requirement, and evaluates the relationship between productivity measurements and the Cole and Cloern (1987) light-biomass model BZ_pI_0.

2.0 Approach

Between 1992 and 2010, MWRA measured primary productivity by phytoplankton at three locations; station F23 at the mouth of Boston Harbor, station N18 a kilometer south of the Mass Bay outfall, and station N04, several kilometers to the northeast of the outfall. Methods and results from MWRA's primary productivity study are in numerous technical reports available on MWRA's website MWRA Environmental Quality Department Technical Reports List (for method details see Libby et al. 2005 Appendix C; results are reported in the annual Water Column Monitoring reports, for example, Libby et al. 2000). Primary production was measured using a small volume/short incubation time method (Lewis and Smith,1983) using procedures from Strickland and Parsons (1972).

In addition to making direct measurements of productivity, MWRA has previously evaluated the performance of light-biomass model BZ_pI_0 (Cole and Cloern 1987) developed to estimate productivity in estuaries. In the BZ_pI_0 model, chlorophyll biomass (B) integrated over the photic depth[1] (Z_p) is multiplied by the amount of sunlight hitting the ocean surface (I_0). In many well mixed estuaries where the amount of available light limits algal growth, the BZ_pI_0 parameter tracks measured algal growth rates well enough to be used as a surrogate for measurements of primary productivity (Cole and Cloern 1987, Keller, 1988).

Comparisons of the modeled $BZpI_0$ parameter to measured productivity for the 1992 through 2000 monitoring years are contained in Kelly and Doering (1995, 1997), Cibik et al. (1996, 1998a, 1998b), and Libby et al. (1999, 2000, 2001). Results of these comparisons have been inconsistent, with measured productivity from some years and stations showing a better fit to the model than others.

A preliminary analysis of more recent data was performed by Shen (2009) who also found that the model fit varied between seasons, years, and stations.

After a thorough review of the previous reports and of the data, we decided to evaluate the relationship between productivity and BZ_pI_0 for the years 2001 through 2010. There were two main reasons for this choice:

- The relationship between the parameters had been evaluated for 1992-2000;
- There are potential comparability issues between the 1992 to 2000 results and the 2001 to 2010 monitoring data for all parameters involved in the evaluation. Among them:

[1] Sunlight is fairly rapidly absorbed as it penetrates seawater, especially in turbid coastal systems. The photic depth is the depth to which enough sunlight penetrates to allow photosynthesis to occur.

- Primary productivity methods changed multiple times during the 1990s. Any comparison for data before 1998 would entail using productivity data generated using very different protocols.
- Chlorophyll and calibrated fluorescence from most of 1998 through the end of 2000 are identified as "use with caution."[2]
- Incident light (Irradiance) data measured by MWRA at the Deer Island Treatment plant roof were only available after 1996.

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[2] This issue was discussed with regulators and the Outfall monitoring Science Advisory Panel in April 2001 (http://www.epa.gov/region1/omsap/omsap0401.html). After identifying the problems, chlorophyll data (and the calibrated fluorescence data that depend on them) were corrected to the extent feasible, but some uncertainties remained.

3.0 Data Selection

In preparation for this report, all light data obtained by MWRA at the Deer Island Treatment Plant were reviewed in their entirety. Several data quality issues were identified, and the entire dataset was calibrated to improve year-to-year comparability in the incident light component of BZ_pI_0 (Appendix A). Since the Deer Island light data were used in the original computation of the areal productivity data from MWRA's ambient monitoring, productivity data were recalculated using the recalibrated light data (Appendix B). Corrected areal productivity data were nearly identical to those originally calculated (Appendix B).

Computation of BZ_pI_0 for the years 2001 through 2010 and pairing those results with concurrent measurements of areal productivity is detailed in Appendix C. That dataset included 325 concurrent determinations of areal productivity and BZ_pI_0. For 24 of those samples, calculated photic zone depth was greater than average water depth for the station. Equation 4 from Brush and Brawley (2009) provides a formula for correcting BZ_pI_0 in these cases.

This correction was evaluated for the MWRA samples but was not applied, because for all 24 cases in which the measured water depth was less than the photic zone depth, the result of the Brush and Brawley (2009) correction was over 95% of the original BZ_pI_0 computation.

Correlation and linear regression analyses between areal productivity and BZ_pI_0 were run using SPSS release 19. Analyses were run on:

- The entire dataset.
- All samples split by year (2001 through 2010)
- All samples split by station (F23, N04, N18)
- All samples split by season (Winter-spring, Summer, and Autumn[3])
- All data split by season and then station

SPSS version 19 was used for the exploratory data analyses. Both BZ_pI_0 and areal productivity showed significant departures from assumptions of normality using the Shapiro-Wilk and Kolmogorov-Smirnov statistics. Log-transformed data also showed departures from normality. The correlation and regression analyses reported below were conducted using both the untransformed and *ln*-transformed data. Results were similar enough that only the untransformed results are discussed below.

Because of the exploratory nature of these analyses, no attempt has been made to correct for multiple comparisons, and significance levels for the statistics have not been tabulated. The large number of regressions run, coupled with the variability in the data, suggest that few if any of the regression slopes determined would differ significantly following a correction for multiple comparisons. Therefore, these slopes are neither tabulated nor discussed.

[3] Seasons are defined as follows: Winter-spring = January-April; Summer = May-August; Autumn = September-December.

4.0 Results

Relationships are discussed as "weak" if the r^2 for the linear regression is less than 0.3, "moderate" if it is between 0.3 and 0.5, and "strong" if the r^2 is greater than 0.5.

Published relationships between BZ_pI_0 and areal productivity tend to be "strong" by these criteria. For example, Cole and Cloern (1987) document r^2 ranging from 0.60 to 0.94. Keller (1988) documented relationships between the parameters in MERL mesocosm experiments and in Narragansett Bay ranging from 0.56 to 0.85. Finally, for the first three years of the MWRA monitoring, Kelly and Doering (1997) documented regressions between these parameters whose r^2 ranged from 0.46 to 0.73.

By these criteria, nine (35%) of the regressions on untransformed data reported in Table 1 were weak, ten (38%) of the regressions were moderate, and seven (27%) of the regressions showed a strong relationship between the parameters.

All samples The regression of BZ_pI_0 on areal productivity for all 325 samples taken together was moderate, with an r^2 of 0.34 (Table 1). As expected for a relationship that explains only 34% of the variability in the data, there is a substantial amount of scatter around the best fit line (Figure 1).

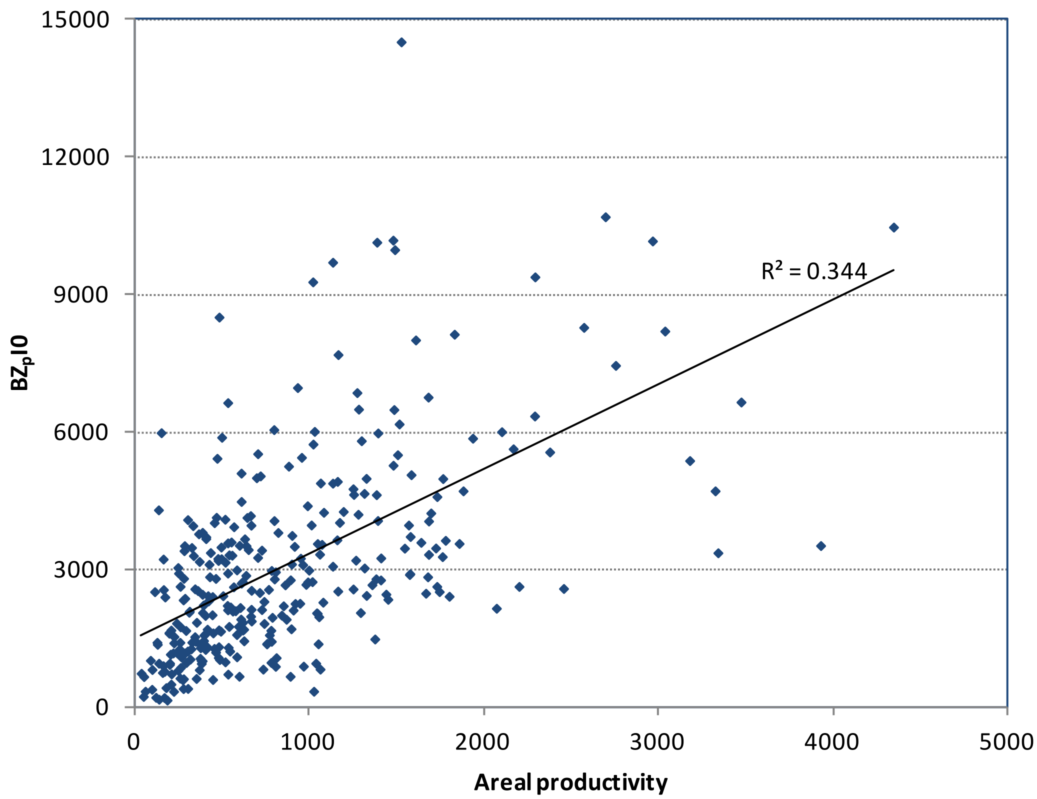

Figure 1. Scatterplot of areal productivity and BZ_pI_0 for all samples and all surveys between 2001 and 2010 (325 samples). Best fit line and r^2 from a linear regression are included. In all plots, areal productivity data have units of mg $C*m^{-2}*day^{-1}$ and BZ_pI_0 has units of µg chl L^{-1} * m * einsteins $m^{-2}day^{-1}$.

Table 1. Correlation coefficients (r) and coefficients of determination (r^2) between Areal productivity and BZpI0 for 2001 to 2010 MWRA monitoring data.

		Raw		Log-transformed		n
		r	r^2	r	r^2	
All data		0.587	0.344	0.637	0.406	325
by Year						
2001		0.732	0.535	0.736	0.541	40
2002		0.7	0.49	0.8	0.639	38
2003		0.676	0.457	0.486	0.236	40
2004		0.791	0.626	0.874	0.763	30
2005		0.668	0.446	0.766	0.587	30
2006		0.604	0.364	0.765	0.585	30
2007		0.37	0.137	0.472	0.223	29
2008		0.319	0.102	0.432	0.187	29
2009		0.321	0.103	0.583	0.34	29
2010		0.772	0.595	0.712	0.507	30
By Station						
F23		0.7	0.491	0.726	0.527	60
N04		0.451	0.204	0.53	0.281	133
N18		0.68	0.462	0.672	0.452	132
By Season						
Spring		0.725	0.525	0.705	0.497	111
Summer		0.326	0.106	0.43	0.184	116
Autumn		0.623	0.388	0.653	0.427	98
By Season and Station						
Spring	F23	0.894	0.8	0.75	0.563	30
	N04	0.566	0.32	0.628	0.395	41
	N18	0.767	0.588	0.673	0.453	40
Summer	F23	0.376	0.141	0.436	0.19	20
	N04	0.33	0.109	0.365	0.133	48
	N18	0.415	0.172	0.598	0.358	48
Autumn	F23	0.655	0.429	0.832	0.692	10
	N04	0.432	0.186	0.556	0.31	44
	N18	0.789	0.623	0.751	0.564	44

Split by year When split by year, most data show moderate to strong regressions, with r^2 ranging between 0.36 and 0.63 for 7 of the 10 years. 2007 through 2009 depart from this pattern, with weak relationships (r^2 less than 0.15) between production and BZ_pI_0 for those years (Table 1, Figure 2).

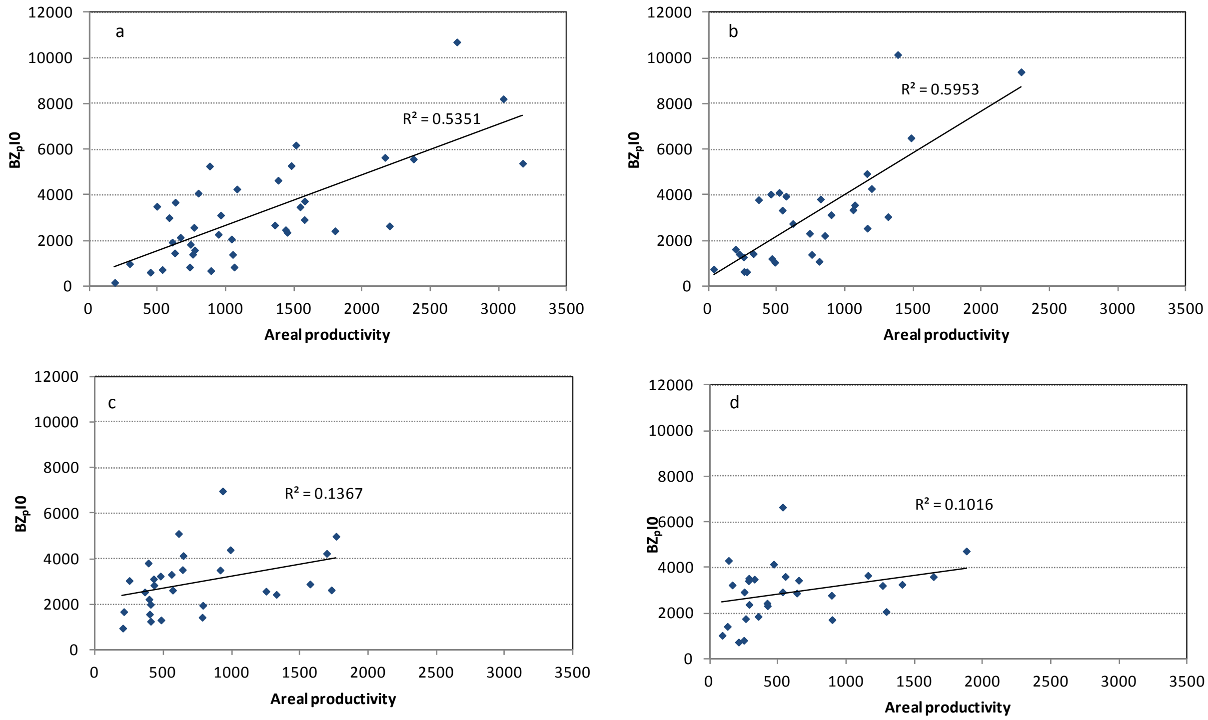

Figure 2. Scatterplots of areal productivity and BZ_pI0 for selected years. In 2001(a) and 2010(b) the linear regression was strong, with an $r^2 > 0.5$. In contrast, in 2007(c) and 2008(d), the linear regression was extremely weak, with an $r^2 < 0.15$.

Split by station When split by station, the data show that across all years, regressions for stations F23 and N18 have an r^2at the high end of the "moderate" range (>0.45). In contrast, the regression for data from station N04 is weak, with an $r^2 = 0.20$ (Table 1, Figure 3).

Split by season When split by season, the data show that spring and fall tend to have moderate to strong relationships between productivity and BZ_pI_0, while the regression for summer data is weak, with the regression explaining only about 10% of the variability in the data (Table 1 Figure 4). This observation is buttressed by the results of the season by station split. All three stations have regressions on summer only data with an $r^2 < 0.2$ (Table 1).

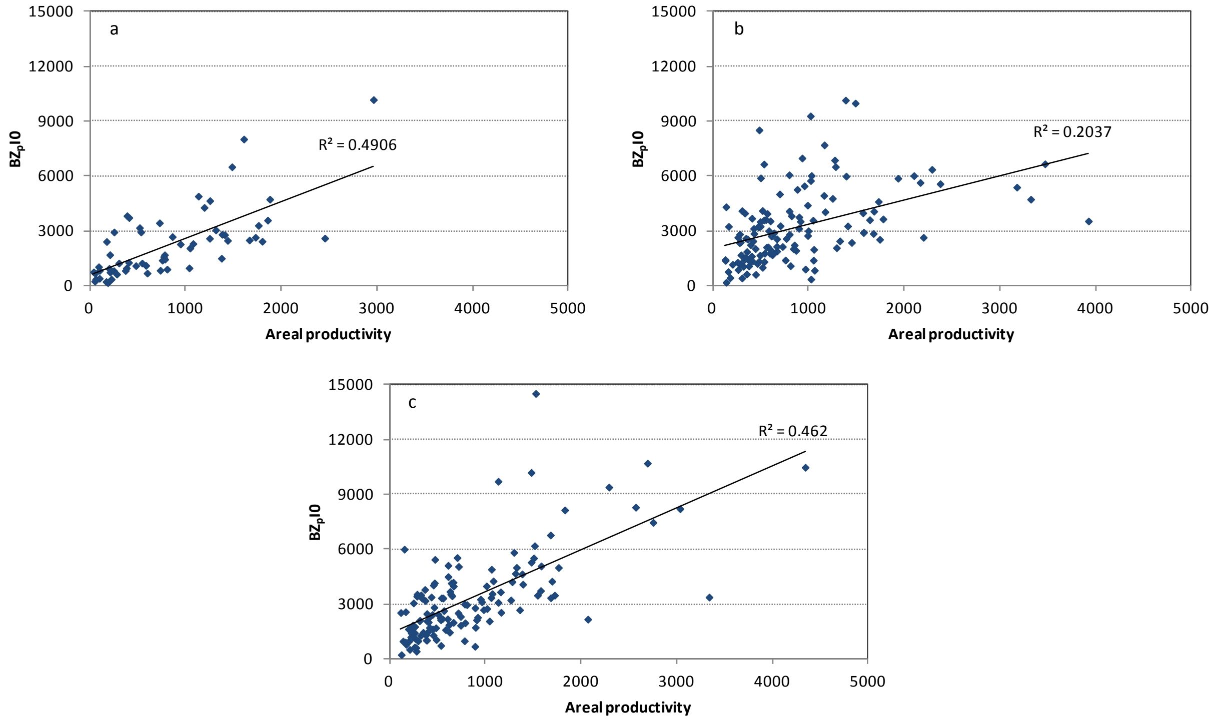

Figure 3. Scatterplots of areal productivity and BZ_pI0 for individual stations. (a) F23(Harbor) (b) N04 (NE Nearfield) (c) N18 (near outfall).

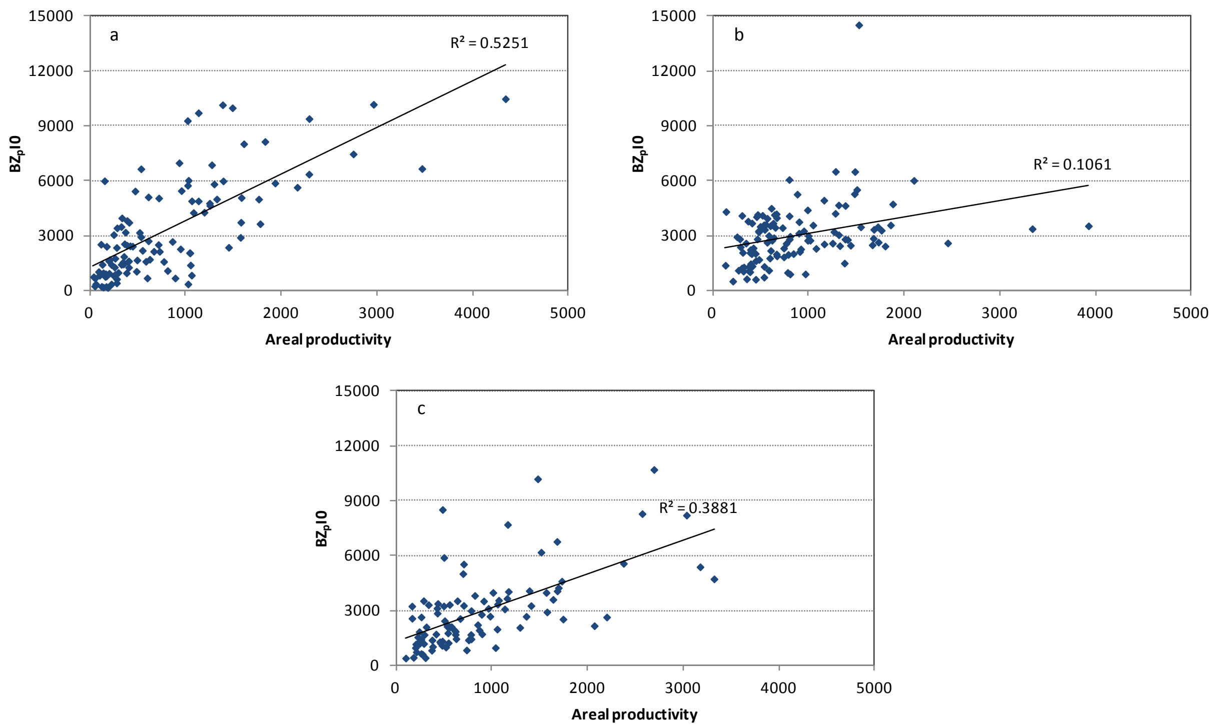

Figure 4. Scatterplots of areal productivity and BZ_pI0 for monitoring seasons. (a) Winter-spring, February to April. (b) Summer, May to August. (c) Autumn, September-December.

Exclusion of summer data After inspecting the results of the split by season and the split by season and by station, the data were filtered to exclude the 116 samples from summer surveys, and the regressions between BZ_pI_0 and areal productivity were repeated for all data, data split by year, and data split by station. These results are presented in Table 2.

The regression between BZ_pI_0 and areal productivity for only winter-spring plus autumn samples for all stations and all years included 209 samples. The strength of the regression was moderate, with an r^2 = 0.45 (Table 2, Figure 5), but was stronger than the regression that included all data (Table 1, Figure 1). A similar result can be observed for the regressions on data split by year and split by station. For all years with moderate or strong regressions between the parameters, the relationship between productivity and BZ_pI_0 is improved by removing the summer data from the regressions. For 2004 the exclusion of summer data results in a substantial improvement in the fit of the data, increasing the r^2 of the regression from 0.63 to 0.90 (Figure 6). In contrast, weak regressions seen between parameters for years 2007 through 2009 for all samples (Table 1) remained weak following the removal of summer data (Table 2).

Table 2. Correlation coefficients (r) and Coefficient of Determination (r^2) between areal productivity and BZ_pI0 for 2001 to 2010 winter-spring and autumn MWRA monitoring data.

	Raw		Log-transformed		n
	r	r^2	r	r^2	
All data	0.675	0.456	0.685	0.47	209
by Year					
2001	0.823	0.677	0.846	0.716	26
2002	0.852	0.726	0.857	0.734	22
2003	0.717	0.514	0.544	0.295	26
2004	0.95	0.902	0.935	0.875	20
2005	0.692	0.479	0.755	0.57	20
2006	0.73	0.533	0.83	0.688	20
2007	0.496	0.246	0.562	0.315	19
2008	0.288	0.083	0.48	0.23	19
2009	0.296	0.088	0.567	0.321	19
2010	0.863	0.745	0.759	0.577	18
By Station					
F23	0.846	0.715	0.708	0.501	40
N04	0.485	0.235	0.592	0.35	85
N18	0.772	0.596	0.7	0.49	84

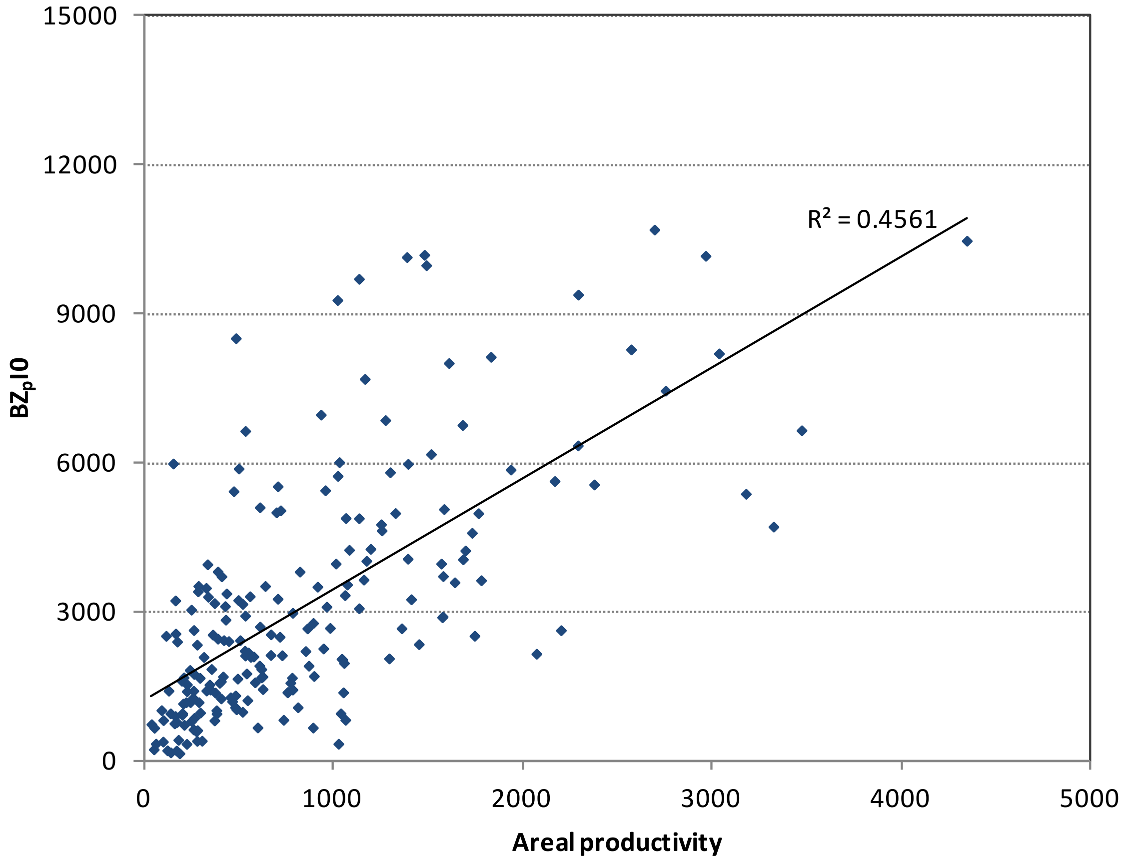

Figure 5. Scatterplot of areal productivity and BZ_pI0 for all samples and all surveys between 2001 and 2010, after the exclusion of summer survey data (209 samples).

Similarly, the removal of summer data noticeably improved the fit between productivity and BZ_pI_0 for results at stations F23 and N18. Regressions on data from those stations both have moderate r^2 when all data are included (Table 1). When summer data are excluded, the regression for station F23 data has a strong relationship with an r^2 of 0.72, while that for data from station N18 has an r^2 of 0.60 (Table 2). The weak relationship between the parameters for data from station N04 is not substantially improved by the removal of summer data, with the r^2 increasing only from 0.20 to 0.24.

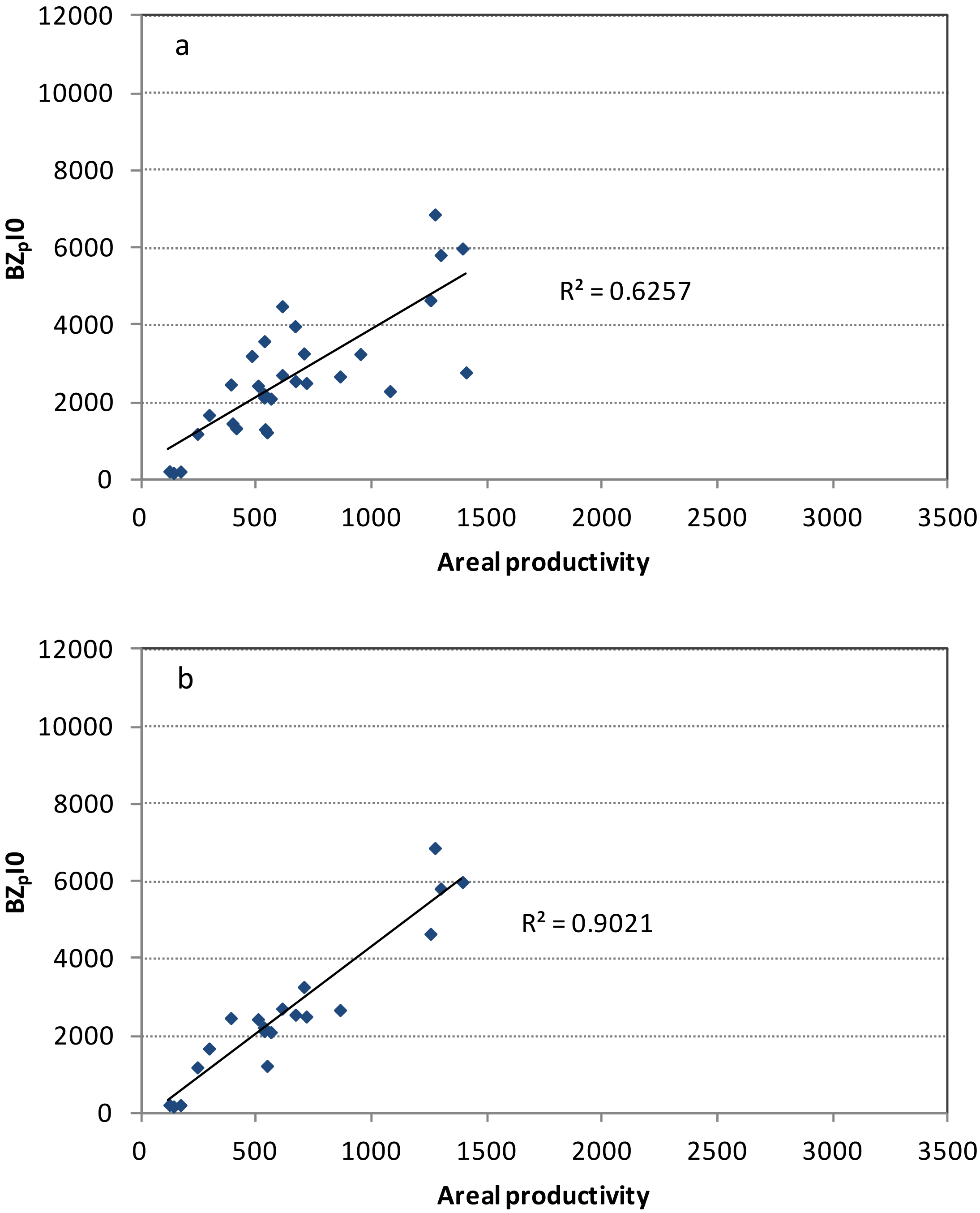

Figure 6. Scatterplot of areal productivity and BZ_pI0 data from 2004, documenting the improvement in the regression when summer data are excluded. (a) All data, $r^2 = 0.63$. (b) Winter-spring and Autumn data only, $r^2 = 0.90$.

5.0 Discussion

In general, the results of this evaluation are consistent with those observed in prior evaluations in MWRA water column monitoring reports, as well as those reported by Shen (2009). Regression model fits vary among seasons, years, and stations, and the coefficients of determination (r^2) are commonly not high enough to use calculated BZ_pI_0 values as a proxy for primary productivity.

Some additional observations can be made from the analyses. First, as mentioned above, the moderate to strong relationships that exist between BZ_pI_0 and productivity for most stations, years, and seasons is not evident for summer data. It is interesting to note that the BZ_pI0 parameter was formulated for well-mixed estuaries, and in Massachusetts Bay during summer the water column is stratified. The lack of relationships observed during summer may reflect water column conditions very different from those in which the composite parameter BZ_pI_0 was developed. When summer data are excluded from the regressions, over half of the regressions in Table 2 show strong r^2 in the ranges reported by other researchers (e.g. Cole and Cloern 1987, Keller 1988).

Another observation is that moderate to strong relationships exist between the parameters for most winter-spring and autumn data from the Harbor station F23 and station N18 in the nearfield. At N04, in contrast, only moderate (spring) to weak (summer, fall) relationships between productivity and BZ_pI_0 were observed. Station N04 at the northeast corner of the nearfield is about 50m deep and somewhat further offshore than N18, which is about 30m deep. Stratification at N04 begins sooner and persists longer As with summer data, it is possible that the general failure of the BZ_pI_0 parameter to reproduce patterns seen in the productivity data from this station may reflect an offshore water column at N04 very different from the systems in which the light-biomass model was developed.

The final observation is that the BZ_pI_0 fit to productivity data is quite variable among years. Even after the exclusion of summer data, the r^2 of annual regressions between productivity and BZ_pI_0 ranged between a low of 0.08 in 2008 to a high of 0.90 in 2004 (Table 2).

The 10-year dataset of paired BZ_pI_0 and primary productivity generated for this review highlights some interesting features of the water column processes in Boston Harbor and Massachusetts Bay. For example, data from station F23 (Figure 4a) show a number of samples with somewhat higher BZ_pI_0 for the measured areal productivity than the "main" cluster of points (Figure 7). These samples were investigated to determine if they might share other distinguishing characteristics. Most of these samples came from winter-spring surveys, though four are from summer surveys. They tend to represent samples that simultaneously contained relatively high chlorophyll and were exposed to relatively high irradiance compared to other samples with similar levels of areal productivity. In other words, the relatively high BZ_pI_0 seen for those samples does not appear to result from any one component in its formulation. Other questions include whether differences in the phytoplankton community (for example, the development or senescence of the *Phaeocystis pouchetii* blooms that tended to occur in late winter-spring) are associated with characteristic differences in BZ_pI_0 or in the areal productivity calculations.

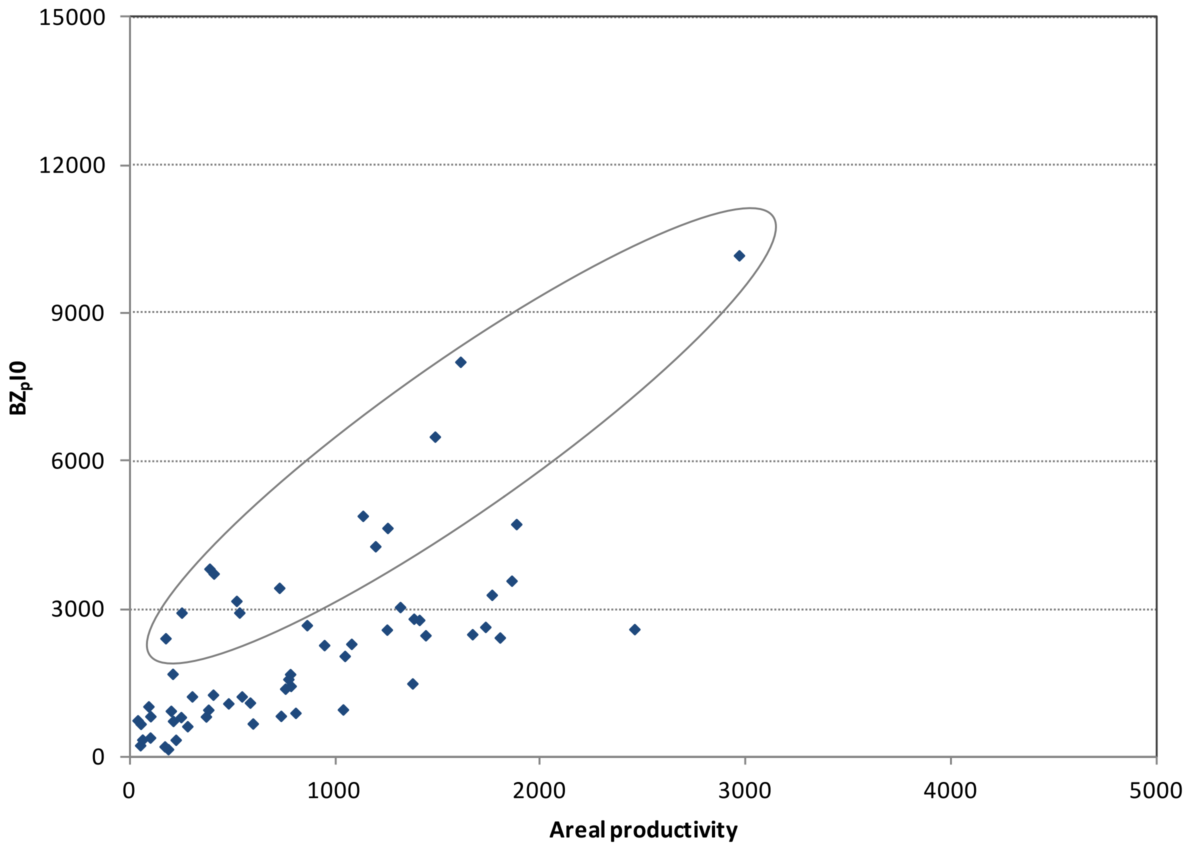

Figure 7. Scatterplot of areal productivity and BZ_pI0 data from Boston Harbor station F23, 2001 to 2010. Samples subjected to additional evaluation are circled.

Other questions include whether differences in the phytoplankton community (for example, the development or senescence of the *Phaeocystis pouchetii* blooms that tended to occur in late winter-spring) are associated with characteristic differences in BZ_pI_0 or in the areal productivity calculations.

6.0 Conclusions

This review was based on the most recently and most comparably obtained light, biomass, photic zone depth and productivity data measured under MWRA's monitoring program. The relationship between areal productivity and the composite parameter BZ_pI_0 does not appear to be consistently strong enough to rely on BZ_pI_0 as a proxy for primary productivity at any given station for a single survey. It does however, show promise for helping evaluate the water column monitoring data.

The variability in the goodness of fit observed in these evaluations is not surprising. The BZ_pI_0 model (Cole and Cloern 1987) is a simple model that uses light and biomass alone to predict phytoplankton production. The model assumes nutrient-replete conditions, and also assumes that phytoplankton biomass is mixed equally through the photic zone. 20 years of MWRA monitoring data document that these assumptions are at least seasonally violated by the waters in Boston Harbor and Massachusetts Bay. The fact that the r^2 values especially during certain years, seasons and at certain stations were so low suggest that at least during certain years, stations and seasons, factors other than light availability and biomass regulated production. These factors might include nutrient availability, or phytoplankton grazing. It makes sense that the model does not track the actual measurements well during summers – when grazing is likely greatest and phytoplankton production in surface waters (in the bay, and maybe in the harbor) is likely nutrient limited.

7.0 References

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8.0 Appendices

Appendices are not included in the printed version of this report but are available on request. Links are provided below.

Appendix A: Correction of 2PI irradiance data from Deer Island meteorological station

Appendix B: Recalculating productivity using revised light data.

Appendix C: Calculating BZpI0.

Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Boston, MA 02129
(617) 242-6000
http://www.mwra.com