Chapter 5.1. Primary productivity patterns and trends

Lead Author
John O’Reilly (Independent consultant, Rhode Island, USA)

Contributing Author
Kenneth Sherman (US National Oceanic and Atmospheric Administration, Northeast Fisheries Science Center)

Chapter Citation
5.1 Primary productivity patterns and trends

SUMMARY

Primary production, the photosynthesis of organic matter, supports and governs all ecosystem production. It drives the flow of energy through food webs in LMEs and is related to the carrying capacity of LMEs for supporting biological diversity, including fisheries resources. High primary productivity is also an indicator of eutrophication (excessive addition of nutrients), which leads to harmful algal blooms and dead zones in coastal waters around the globe. Ocean primary productivity is responsive to global warming and is closely coupled to climate variability.

Satellite ocean colour data sets covering 16 years (1998 to 2013) were used to estimate average annual primary productivity and chlorophyll (the green pigment involved in photosynthesis) in the world’s 66 LMEs and the Western Pacific Warm Pool (WPWP). Daily primary productivity and chlorophyll levels over the entire global ocean were estimated at a spatial resolution of approximately 9 km. Inputs to the productivity model included ocean colour data files from five satellite sensors. Results were used to rank LMEs according to their 16-year average primary productivity. LMEs were then divided into five groups based on these rankings. The confidence level of the primary productivity estimates is high where sampling is adequate, which is the case for most LMEs. Measurements from one satellite sensor were used to estimate 11-year (2003 to 2013) trends in chlorophyll. Accurate assessments of primary productivity and chlorophyll based on satellite data were not feasible for eight high-latitude LMEs, due to low spatial coverage or low sampling frequency. Surveys from ships or airplanes provide better results for these regions.

Key messages

1. Most relatively high values of primary productivity in the global ocean are in coastal waters, within LME boundaries. Across the entire global ocean, average annual primary productivity (1998 to 2013) ranges over three orders of magnitude, while it varies by one order of magnitude in the 66 LMEs and the WPWP (from 74 to 755 grams of carbon per m² per year). Average chlorophyll concentrations show the same pattern of global distribution.
   - LMEs with highest primary productivity: Baltic Sea (highest), Yellow Sea, North Brazil Shelf, Black Sea, Gulf of California, North Australian Shelf, and Arabian Sea.
   - LMEs with lowest primary productivity: Insular Pacific Hawaiian (lowest), Southwest Australian Shelf, Northeast Australian Shelf, Mediterranean Sea, East Central Australian Shelf, and East Brazil Shelf, plus the WPWP.

2. No large-scale, consistent pattern of either increase or decrease in chlorophyll was observed (2003 to 2013). There are 36 LMEs with increasing trends in chlorophyll (measured as chlorophyll a) and 31 with decreasing trends. Trends are weakly correlated with latitude, and most are not statistically significant (P<0.05).
   - LMEs with significant increasing chlorophyll trends: Scotian Shelf, Patagonian Shelf, Labrador Newfoundland, and Southeast Australian Shelf LMEs (trends over 11 years of 20, 20, 13, and 1 per cent, respectively). The Baltic Sea LME had a relatively high chlorophyll increase (48 per cent), but this trend is not significant.
   - LMEs with significant decreasing chlorophyll trends: Indonesian Sea, Oyashio Current, and Celtic-Biscay Shelf (trends of -16, -8, and -4 per cent over 11 years, respectively).
5.1.1 Introduction

Primary production, the photosynthesis of organic matter, supports and governs all ecosystem production and plays a pivotal role in ecosystem nutrient and carbon cycling and budgets (Hofmann et al. 2008). Primary production drives the trophodynamics (flow of energy through food webs) of LMEs and can be related to the carrying capacity of marine ecosystems for supporting fish resources (Christensen et al. 2009; Pauly and Christensen 1995).

Measurements of ecosystem primary productivity are useful indicators of the growing eutrophication problem that is leading to an increase in the frequency and extent of dead zones in coastal waters around the globe (Diaz and Rosenberg 2008). In several LMEs, excessive nutrient loadings have produced harmful algal blooms implicated in mass mortalities of marine resource species, emergence of pathogens (for example, cholera, vibrios, red tides, and paralytic shellfish toxins) and population explosions of invasive species (Epstein 2000).

Indicators of changing productivity are based on the following physical attributes and biogeochemical constituents: photosynthetically active radiation, water column transparency, chlorophyll \(a\), primary production, zooplankton biomass, species biodiversity, ichthyoplankton (eggs and larvae of fish) biodiversity, oceanographic variability (for example, temperature, salinity, density, circulation, and nutrient flux) (Sherman et al. 2009; Sherman et al. 1998; Sherman 1980), and acidification (Oliver et al. 2012). Plankton can be measured over decadal time scales by deploying Continuous Plankton Recorder systems monthly across LMEs from commercial vessels of opportunity (Jossi and Kane 2013; Batten et al. 2003; Jossi et al. 2003). Advanced plankton samplers can be fitted with electronic sensors for temperature, salinity, chlorophyll, nutrients, oxygen, and light (Melrose 2006). Application of satellite-derived data, coupled with appropriate algorithms, can allow time-series visualizations of LME-scale sea surface temperature, hydrographic fronts (boundaries between water masses with different physical properties), chlorophyll concentrations, and primary productivity estimates (Sherman et al. 2011).

Chlorophyll \(a\), the principal pigment in phytoplankton, can be estimated in surface water from satellite ocean colour sensors by using the blue-green part of the ocean colour spectrum (O’Reilly et al. 2000 and 1998). Chlorophyll \(a\) is an index of phytoplankton abundance, and, together with light and nutrients, is among the key factors in primary productivity.

5.1.2 Data and methodologies

5.1.2.1 Chlorophyll \(a\) and primary productivity estimates

The average levels of chlorophyll \(a\) and primary productivity for the world’s 66 LMEs and the Western Pacific Warm Pool (WPWP) were characterized for a 16-year period (1998 to 2013) using 76 028 satellite data files at a resolution of 9 km. These data are from five sensors: 1) the Ocean Color and Thermal Sensor (OCTS); 2) Sea-viewing Wide Field-of-view Sensor (SeaWiFS); 3) Moderate Resolution Imaging Spectroradiometer on the AQUA satellite (AQUA); 4) Moderate Resolution Imaging Spectroradiometer on the TERRA satellite (TERRA); and 5) the medium-spectral-resolution imaging spectrometer (MERIS), along with the Ocean Production from the Absorption of Light (OPAL) productivity model. Primary productivity is expressed as grams of carbon per m\(^2\) per year. Measurements of primary productivity per unit volume of seawater are integrated over the upper layer of the water column to estimate grams of carbon produced per unit area of the ocean.

Satellite chlorophyll data are the standard chlorophyll products provided by the US National Aeronautics and Space Administration’s Goddard Space Flight Center (NASA-GSFC) from the most recent (2012) major data reprocessing, based on Version 6 of the OC-maximum band ratio algorithms (NASA 2013). The correlation between \textit{in situ} chlorophyll \(a\) and chlorophyll \(a\) estimates from SeaWiFS (0.909) and MODIS-AQUA (0.925) is relatively high, and the regression slopes between \textit{in situ} and satellite data are close to 1.0 (NASA 2013). Chlorophyll concentrations are expressed as milligrams per m\(^3\) of seawater in the surface layer (the upper metre of the ocean).
Daily estimates of global primary productivity were calculated using the OPAL model, a derivative of the model first formulated by Marra et al. (2003). Four key satellite data inputs to OPAL are: 1) the concentration of surface chlorophyll \(a\), 2) sea surface temperature, 3) photosynthetically active radiation striking the ocean surface, and 4) the absorption of light by coloured dissolved organic matter. Agreement is excellent between \textit{in situ} \(^{14}\text{C}-\text{based}\) measurements from MARMAP surveys (O’Reilly et al. 1987) and productivity estimates from OPAL in the Northeast US Continental Shelf LME, where \textit{in situ} productivity measurements were made throughout the ecosystem during most months (Table 5.1).

<table>
<thead>
<tr>
<th>Source of estimate</th>
<th>Sample size</th>
<th>Years</th>
<th>Productivity (grams of carbon per m(^2) per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ measurements</td>
<td>1 243</td>
<td>1977–1982</td>
<td>355</td>
</tr>
</tbody>
</table>

A total of 76 028 satellite standard mapped image files from five NASA-GSFC satellite ocean colour sensors (OCTS, SeaWiFS, MODIS-AQUA, MODIS-TERRA and MERIS) were used to derive daily estimates of primary productivity over the global ocean. Merging data from these five ocean colour sensors resulted in minimal data gaps in the global productivity estimates, except in 1997. Because sampling was incomplete in 1997 and 2014, average chlorophyll \(a\) and primary productivity estimates are based on the 16-year period from 1998 through 2013.

Sampling by satellite ocean colour sensors is inadequate for a comprehensive characterization of chlorophyll \(a\) and primary productivity in the most northern and southern LMEs with short growing seasons, persistent ice or clouds, and partial coverage by satellite sensors that rely on daylight for ocean colour measurements. Gregg and Casey (2007) documented the positive biases in chlorophyll data from ocean colour sensors. Nevertheless, the results for these LMEs, while biased and incomplete, are presented for comparison. \textit{In situ} measurements would be required for more accurate assessment of the productivity and the timing of annual peaks and minima for these systems.

### 5.1.2.2 Detecting time trends in chlorophyll \(a\)

Trends in chlorophyll \(a\) are based on data from one sensor (MODIS-AQUA), for the 11-year period 2003 through 2013. Data from one sensor were used instead of the merged data from five sensors to minimize sensor-to-sensor biases in the trends. Trends were computed based on linear regressions of the yearly anomalies in annual mean chlorophyll \(a\), following the methods outlined by Gregg et al. (2005). Tests of whether linear regression slopes differ significantly from zero (no trend) at the 0.95 probability level were computed using the T-Test statistic (Sokal and Rohlf 1995).

Trends in chlorophyll \(a\) were calculated as relative per cent change from 2003 to 2013, computed from the predicted values \((P)\) from the linear regression of annual mean chlorophyll \(a\) versus year as follows:

\[
\text{relative percentage change} = 100 \times \frac{\text{last}(P) - \text{first}(P)}{\text{first}(P)}.
\]

### 5.1.3 Major findings, discussion, and conclusions

#### 5.1.3.1 Spatial patterns in chlorophyll and primary production

Mean chlorophyll \(a\) throughout the global ocean varies from 0.008 to 100 milligrams per m\(^3\), a range of more than four orders of magnitude (Figure 5.1). Relatively high chlorophyll \(a\) values (those exceeding 1 to 3 milligrams per m\(^3\)) are found near shore, within LME boundaries. Mean chlorophyll \(a\) is less than 0.02 milligrams per m\(^3\) in the South Pacific Gyre, the Earth’s largest oceanic desert, located west of South America at about 25°S latitude (Claustre and Maritorena 2003).
Mean primary production per year (Figure 5.2) ranges over three orders of magnitude, from 1.6 grams of carbon per m² per year (at 17.92°S, 142.17°W) to 6,382 grams of carbon per m² per year (at 6.00°S, 12.33°E, the Guinea Current). As with chlorophyll a, the highest primary productivity values (those exceeding 300 grams of carbon per m² per year) are found in coastal waters within LME boundaries.

5.1.3.2 Global primary production

The average annual global ocean primary production for the 16-year period 1998 to 2013, based on five sensors and estimated through OPAL, is 52 x 10¹⁵ grams of carbon per year. This is lower than the estimate by Behrenfeld et al. (2005) of 60 x 10¹⁵ grams of carbon per year, an estimate based on the Vertically Generalized Production Model and SeaWiFS data for the six-year period 1997 to 2002. The OPAL global production estimate is higher than the estimate of 36.5 to 45.6 x 10¹⁵ grams of carbon per year by Antoine et al. (1996), an estimate based on coastal zone colour data from 1978 to 1986. These global estimates are calculated by integrating primary production values (grams of carbon per m²) over the entire area of the ocean.

5.1.3.3 Classification of LMEs into five groups

It is important to know the productivity status of marine ecosystems, because the magnitude of primary productivity is related to ecosystem services such as fishery production (Rosenberg et al. 2014). High primary productivity is generally regarded as a positive ecosystem attribute, except when it results in hypoxia (low oxygen) from decomposing phytoplankton blooms stimulated by anthropogenic nutrient pollution in rivers.

The 66 LMEs and the WPWP were arranged into five groups based on their 16-year mean primary productivity values. There are no a priori criteria for grouping primary productivity into discrete ranges, and no established thresholds for indicating either impoverished or excessive levels of primary productivity in open water. Moreover, while the terms ‘oligotrophic’, ‘mesotrophic’ and ‘eutrophic’ are frequently used in the scientific literature, quantitative definitions of primary productivity levels are lacking. Consequently, a statistical approach was used to classify ecosystem primary productivity into five groups, based on the 0, 10, 25, 75, 90, and 100 percentiles.
Figure 5.2 Distribution of average annual primary productivity throughout the global ocean, 1998–2013. Primary productivity, the photosynthesis of organic matter by phytoplankton that supports and governs all ecosystem production, ranges from 74 to 755 grams of carbon per m\(^2\) per year in the LMEs studied. Most relatively high values of primary productivity in the global ocean are in coastal waters, within LME boundaries.

Values shown are mean net primary productivity per year, based on the OPAL model and satellite ocean colour data; LME boundaries are outlined in white.

Figure 5.3 Classification of 66 LMEs and the WPWP into five groups by productivity. A statistical approach was used to classify the 16-year average primary productivity into five groups, based on the 0, 10, 25, 75, 90, and 100 percentiles. Most (33) LMEs are in the middle range of primary productivity, Group 3. Figure 5.4 maps the distribution of these productivity groups.

![Classification of 66 LMEs and the WPWP into five groups by productivity](image-url)

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of LMEs</th>
<th>Productivity range (g of carbon per m(^2) per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>76–107</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>107–137</td>
</tr>
<tr>
<td>3</td>
<td>33</td>
<td>137–181</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>181–331</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>331–441</td>
</tr>
</tbody>
</table>

Classification is based on the magnitude of 16-year mean levels of net annual primary productivity; LMEs are ordered by primary productivity in each group, with the most productive at top.
Most LMEs are in the middle range of primary productivity, Group 3, between the 25th and 75th percentiles (Figure 5.3). The seven LMEs with the highest primary productivity, Group 5, are the Baltic Sea, Yellow Sea, North Brazil Shelf, Black Sea, Gulf of California, North Australian Shelf and the Arabian Sea. The seven areas with the lowest primary productivity, Group 1, are six LMEs: Insular Pacific-Hawaiian, Southwest Australian Shelf, Northeast Australian Shelf, Mediterranean, East Central Australian Shelf, and East Brazil Shelf, as well as the Western Pacific Warm Pool. The global distribution of LMEs and the WPWP in these five primary productivity classification groups is mapped in Figure 5.4.

5.1.3.4 LME trends

No large-scale, consistent pattern of either increase or decrease in chlorophyll $a$ was observed, with most chlorophyll $a$ trends being near zero (Figure 5.5). There are 36 LMEs with positive chlorophyll $a$ trends and 31 with negative chlorophyll $a$ trends from 2003 to 2013. Trends are weakly correlated with latitude. The four LMEs with statistically significant increasing chlorophyll $a$ trends at the 0.95 per cent probability level are the Scotian Shelf, Patagonian Shelf, Newfoundland-Labrador Shelf, and Southeast Australian Shelf (increases of 20, 20, 13, and 1 per cent over the 11-year period, respectively). The Baltic Sea LME shows relatively higher chlorophyll $a$ increases (48 per cent), but this trend is not statistically significant. The three LMEs with statistically significant decreasing chlorophyll $a$ trends are the Indonesian Sea, Oyashio Current, and Celtic-Biscay Shelf (decreases of 16, 8, and 4 per cent over 11 years, respectively). These results are similar to those presented in an earlier UNEP report (Sherman and Hempel 2008), where nine-year trends were statistically significant in only four LMEs.

There were relatively few monthly samples from ocean colour sensors in the most northerly and southerly latitudes from 1998 to 2013 (Figure 5.6). Eight LMEs had less than 60 per cent spatial coverage, or were sampled during less than 60 per cent of the 192 months from 1998 to 2013 (Figure 5.7). These LMEs are: Antarctica, Kara Sea, Laptev Sea, East Siberian Sea, Beaufort Sea, Canadian High Arctic-North Greenland, Central Arctic, and Northern Bering-Chukchi Seas. It is therefore unlikely that the status and trends in chlorophyll $a$ and primary productivity described in this report for these eight LMEs are reliable or represent true ecosystem conditions. For these ecosystems, remotely-sensed ocean colour measurements, for example from aircraft (Hugo et al. 2005; Harding et al. 1992), or in situ measurements, would be required for more accurate indices of their productivity, phenology and trends.
Figure 5.5 Trends in chlorophyll a (2003–2013) in relation to latitude. No large-scale, consistent pattern of either increase or decrease in chlorophyll a was observed. There are 36 LMEs with positive chlorophyll a trends and 31 with negative chlorophyll a trends, and trends are weakly correlated with latitude. The four LMEs with statistically significant increasing chlorophyll a trends (red circles to the right of the purple line) are the Scotian Shelf (#8), Patagonian Shelf (#14), Newfoundland-Labrador Shelf, and Southeast Australian Shelf. The three LMEs with statistically significant decreasing chlorophyll a trends (red circles to the left of the purple line) are the Indonesian Sea (#38), Oyashio Current, and Celtic-Biscay Shelf.

Figure 5.6 Global distribution of chlorophyll a samples, 1998–2013. The confidence level of the primary productivity estimates is high where sampling is adequate, which is the case for most LMEs. However, sampling by satellite ocean colour sensors was inadequate for a comprehensive characterization of chlorophyll a and primary productivity in northern and southern LMEs with short growing seasons, persistent ice or clouds, and partial coverage by satellite sensors that rely on daylight for ocean colour measurements.
Trends in primary productivity would be expected to follow trends in chlorophyll $a$ since chlorophyll $a$ is a dominant input to the OPAL productivity model and their averages are correlated (correlation coefficient $= 0.63$).

### 5.1.3.5 Limitations and qualitative confidence in the LME productivity indicators

The overall confidence level in the primary productivity indices is high where sampling is adequate, which is the case for most LMEs. The reasons for this confidence level are:

1. The measurement consistency is high within and among LMEs.
2. Ocean colour satellite data provide a very large statistical sample size of approximately 10 000 pixels for each LME.
3. Where both in situ productivity measurements and satellite measurements were made throughout the ecosystem and during most months, such as in the Northeast US Continental Shelf, the agreement is excellent between conventional in situ 14C-based measurements of productivity and productivity indicators from the OPAL model (see Table 5.1).
4. The estimate of annual global ocean production from OPAL ($52 \times 10^{15}$ grams of carbon per year) is in agreement with the range previously reported in the scientific literature.

The major limitation of the LME productivity indicators is incomplete sampling, which is the result of inadequate spatial or seasonal coverage of the LMEs by satellite ocean colour sensors. These sensors rely on daylight and cloud-free conditions for measurements of chlorophyll and other variables in surface water. Estimates of ecosystem productivity based on satellite data, and models such as OPAL, rely heavily on these satellite ocean colour chlorophyll estimates and photosynthetically active radiation data. These estimates and models therefore have similar spatial and seasonal limitations.
References


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